LOAN DOCUMENT

PHOTOGRAPH THIS SHEET

DTIC ACCESSION NUMBER

LEVEL

0

INVENTORY

Vol. 1

Installation of Air Sparging & Soil . . .

DOCUMENT IDENTIFICATION

16 Mar 98

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

DISTRIBUTION STATEMENT

ACCESSION FOR
NTIS GRA&I
DTIC TRAC
UNANNOUNCED
JUSTIFICATION

BY

DISTRIBUTION/

AVAILABILITY CODES

DISTRIBUTION	AVAILABILITY AND/OR SPECIAL	
A-1		

DISTRIBUTION STAMP

DATE ACCESSIONED

DATE RETURNED

20001130 021

DATE RECEIVED IN DTIC

REGISTERED OR CERTIFIED NUMBER

PHOTOGRAPH THIS SHEET AND RETURN TO DTIC-FDAC

H A N D L E W I T H C A R E

DTIC FORM JUN 90 70A

DOCUMENT PROCESSING SHEET

PREVIOUS EDITIONS MAY BE USED UNTIL STOCK IS EXHAUSTED.

LOAN DOCUMENT

DRAFT REPORT

VOLUME I

DRAFT
PILOT TEST REPORT

INSTALLATION OF AIR SPARGING AND SOIL VAPOR EXTRACTION SYSTEMS AT SITES SS-06, SS-08 & ST-40

WURTSMITH AIR FORCE BASE
OSCODA, MICHIGAN

CONTRACT No. F41624-94-D-8066
DELIVERY ORDER 0007

March 16, 1998

PREPARED FOR:
AIR FORCE CENTER FOR ENVIRONMENTAL EXCELLENCE
BROOKS AFB, TEXAS

AQM01-01-0370

DEFENSE TECHNICAL INFORMATION CENTER
REQUEST FOR SCIENTIFIC AND TECHNICAL REPORTS

Title AFCEE Collection

1. Report Availability *(Please check one box)*

☒ This report is available. *Complete sections 2a - 2f.*

☐ This report is not available. *Complete section 3.*

2a. Number of Copies Forwarded 1 each

2b. Forwarding Date July/2000

2c. Distribution Statement *(Please check ONE box)*

DoD Directive 5230.24, "Distribution Statements on Technical Documents," 18 Mar 87, contains seven distribution statements, as described briefly below. Technical documents MUST be assigned a distribution statement.

☒ DISTRIBUTION STATEMENT A: Approved for public release. Distribution is unlimited.

☐ DISTRIBUTION STATEMENT B: Distribution authorized to U.S. Government Agencies only.

☐ DISTRIBUTION STATEMENT C: Distribution authorized to U.S. Government Agencies and their contractors.

☐ DISTRIBUTION STATEMENT D: Distribution authorized to U.S. Department of Defense (DoD) and U.S DoD contractors only.

☐ DISTRIBUTION STATEMENT E: Distribution authorized to U.S. Department of Defense (DoD) components only.

☐ DISTRIBUTION STATEMENT F: Further dissemination only as directed by the controlling DoD office indicated below or by higher authority.

☐ DISTRIBUTION STATEMENT X: Distribution authorized to U.S. Government agencies and private individuals or enterprises eligible to obtain export-controlled technical data in accordance with DoD Directive 5230.25, Withholding of Unclassified Technical Data from Public Disclosure, 6 Nov 84.

2d. Reason For the Above Distribution Statement *(in accordance with DoD Directive 5230.24)*

2e. Controlling Office HQ AFCEE

2f. Date of Distribution Statement Determination 15 Nov 2000

3. This report is NOT forwarded for the following reasons. *(Please check appropriate box)*

☐ It was previously forwarded to DTIC on .... *(date)* and the AD number is ....

☐ It will be published at a later date. Enter approximate date if known. ....

☐ In accordance with the provisions of DoD Directive 3200.12, the requested document is not supplied because:

....

Print or Type Name Laura Peña

Signature Laura Peña

Telephone 210-536-1431

(For DTIC Use Only)
AQ Number M01-01-0370

DRAFT

PILOT TEST REPORT

FOR

INSTALLATION OF AIR SPARGING AND SOIL VAPOR EXTRACTION SYSTEMS AT SITES SS-06 AND SS-08

WURTSMITH AIR FORCE BASE

OSCODA, MICHIGAN

Contract No. F41624-94-D-8066

Delivery Order 0007

March 16, 1998

Prepared for:

Air Force Center for Environmental Excellence
Brooks Air Force Base, Texas

Prepared By:

AmTech Engineering, Inc.
4343 Saguaro Trail
Indianapolis, Indiana 46268

TABLE OF CONTENTS

VOLUME I

LIST OF FIGURES

LIST OF TABLES

VOLUME II

LIST OF APPENDICES

LIST OF ACRONYMS AND ABBREVIATIONS

ACC	Air Combat Command
AFB	Air Force Base
AFCEE	Air Force Center For Environmental Excellence
AmTech	AmTech Engineering, Inc.
AREFS	Air Refueling Squadron
AS	Air Sparging
ASCE	American Society of Civil Engineers
AST	Aboveground Storage Tank
bgs	Below Ground Surface
BMW	Bombardment Wing
BRAC	Base Realignment and Closure Cleanup Plan
BTEX	Benzene, Toluene, Ethylbenzene and Xylenes
DCE	Dichloroethylene
DO	Delivery Order, Dissolved Oxygen
DQOs	Data Quality Objectives
DRMO	Defense Reutilization and Marketing Office
EIS	Environmental Impact Statement
EOD	Explosive Ordnance Disposal
ERB	Environmental Review Board
FS	Feasibility Study
GC	Gas Chromatography
GC/MS	Gas Chromatographic/Mass Spectra
GFAA	Graphite Furnace Atomic Absorption
gpm	gallon per minute
GPR	Ground Penetrating Radar
ICF	ICF Technology, Inc.
ICP	Inductively Coupled Plasma
LCS	Laboratory Control Samples
LEL	Lower Explosive Limit
LNAPL	Light Non Aqueous Phase Liquid
M&E	Metcalf & Eddy, Inc.
MCL	Maximum Contaminant Level
MDEQ	Michigan Department of Environmental Quality
MS/MSD	Matrix Spike/Matrix Spike Duplicate
NPL	National Priorities List
ORP	Oxidation Reduction Potential
OWTP	Oscoda Wastewater Treatment Plant
P&ID	Process and Instrumentation Diagram
PCE	Tetrachloroethene (Per chloroethene)
PID	Photoionization Detector
PNA/PAH	Polynuclear Aromatic Hydrocarbons
POL	Petroleum, Oil and Lubricants
PPE	Personal Protective Equipment
ppmv	parts per million vapor

LIST OF ACRONYMS AND ABBREVIATIONS (continued)

ppm	parts per million
psi	pounds per square inch
QA/QC	Quality Assurance/Quality Control
QAPP	Quality Assurance Program Plan
QPP	Quality Program Plan
RAP/DD	Remedial Action Plan/Decisions Document
RI	Remedial Investigation
SAC	Strategic Air Command
SAP	Sampling and Analysis Plan
scfm	Standard Cubic Feet per Minute
SVE	Soil Vapor Extraction
SVOC	Semi-Volatile Organic Compound
TCE	Trichloroethene
TCLP	Toxicity Characteristic Leaching Procedure
TDS	Total Dissolved Solid
TPH	Total Petroleum Hydrocarbon
TVH	Total Volatile Hydrocarbon
USAF	United States Air Force
USGS	United States Geological Survey
UST	Underground Storage Tank
V&V	Verification and Validation
VOC	Volatile Organic Compound
WAFB	Wurtsmith Air Force Base
WWES	WW Engineering and Science, Inc.

EXECUTIVE SUMMARY

This report describes the methods and results of air sparging (AS) and soil vapor extraction (SVE) tests conducted at Sites SS-06 and SS-08 at the Wurtsmith Air Force Base (WAFB) in Oscoda, Michigan. This project was completed on behalf of the Air Force Center for Environmental Excellence/Environmental Review Board (AFCEE/ERB), Brooks AFB, Texas, under prime contract number F41624-94-8006/DO-0007. The project was completed by AmTech Engineering, Inc. (AmTech) with Metcalf & Eddy, Inc. (M&E) as the principal subcontractor.

SITE DESCRIPTION

WAFB is located in Iosco County, in northeastern Michigan, in the township of Oscoda. The Base is bordered on the northeast by Van Etten Lake, on the northwest, west, and south by the Au Sable State Forest, and on the east by the community of Oscoda, Michigan. The Base was initially established as Camp Skeel in 1924 when the Army Air Service began using the Base as a gunnery range and for winter maneuvers. WAFB became a Base Realignment and Closure (BRAC) II site when it was officially closed on June 30, 1993 (Air Force Base Conversion Agency, 1995). Since that time, various studies and investigations of potential environmental problems and their remediation have been ongoing. The Base is currently maintained by a caretaker force.

PREVIOUS INVESTIGATIONS

Groundwater and soil investigations have been ongoing at Sites SS-06 and SS-08 since the early 1980s. This work culminated in the feasibility study (FS) and remedial action plan/decision document (RAP/DD) produced for these sites by ICF Technology, Inc. (ICF) in 1996 and 1997.

Site SS-06

Site SS-06 includes four former and three existing above ground storage tanks (ASTs) and two underground storage tanks (USTs) at the Petroleum, Oils, and Lubricants Bulk Storage Facility (POL). No significant fuel spills have been reported at the POL Bulk Storage Facility; however, Tank 7000, a 1.2-million-gallon above-ground storage tank for JP-4 has leaked in the past. A groundwater plume containing JP-4 (jet fuel) constituents was discovered in 1983 extending northeast from the POL area. The Benzene Plant pump-and-treat system, made operational in January 1992, was designed to capture the groundwater plume. The plant is currently in operation and consists of four purge wells, two air-stripper towers, thermal off-gas treatment and a free-phase LNAPL recovery system. The trend for contaminants in groundwater captured by this system is that of a slight decrease in concentration over the period of operation of the plant.

In 1994 ICF conducted a remedial investigation of the POL area. A soil gas investigation was conducted in the area of Site SS-06 to assess the extent of JP-4 contamination in the soil. The soil gas survey detected VOCs and SVOCs.

A soil gas survey and bioventing pilot test were completed by Parsons Engineering Science, Inc. (Parsons ES) in July 1996 in the POL. The study area included a portion of Site SS-06 within and immediately around the diked AST area which included Tank 7000 (Figure 1-7) The study by Parsons ES indicated that bioventing was a feasible remediation technology for the site and a full scale implementation of the bioventing system was completed in August 1996 (Parsons ES, 1996).

In 1997 ICF prepared a Draft Final FS (ICF, 1997B), and in 1996 a Draft RAP/DD (ICF, 1996) for Site SS-06. The RAP/DD (ICF, 1996) proposed AS/SVE as the preferred alternative for remediating the residual LNAPL contamination in groundwater and soils at the water table in the area between the Parsons ES bioventing system and the Benzene Plant Pump and Treat

System recovery wells. The RAP/DD assumed SVE radius of influence was 50 feet and the assumed AS radius of influence was 25 feet

Site SS-08

From 1979 to 1981, the United States Geological Survey (USGS) did a preliminary groundwater study at Site SS-08. Trichloroethene (TCE), dichloroethylene (DCE) and benzene were each detected in the groundwater samples which were collected (USGS, 1983).

In September 1988, a leaking fuel line was found at hydrant 22A. In October 1988, contaminated soil was excavated from the area around the leaking fuel line fitting, and the Michigan Department of Environmental Quality (MDEQ) collected groundwater samples at the site. The analysis of these samples showed concentrations of benzene, toluene, ethylbenzene, and xylenes (BTEX) that confirmed impact to the groundwater.

In 1994 and 1995, ICF conducted a remedial investigation of Site SS-08, which focused on the areas to the south of the SAC Operational Apron, including the hangars and associated oil/water separators (ICF, 1995). The ICF investigation included soil gas, surface and subsurface soil, and groundwater sampling for the analysis of VOCs. No contaminants were detected in any of the surface or subsurface soils at concentrations exceeding MDEQ residential or industrial criteria. There were VOCs detected in some of the groundwater samples that exceeded MDEQ residential and industrial criteria and federal MCLs (ICF, 1995).

ICF prepared a Final Remedial Action Plan/Decision Document (ICF, 1997A) addressing three groundwater "hot spots" identified within Site SS-08. The RAP/DD (ICF, 1997A) proposed AS/SVE as the preferred alternative for remediating the residual groundwater contamination at Site SS-08. The assumed radius of influence for air sparging wells was 25 feet and the assumed radius of influence for vapor extraction wells was 50 feet.

CLEAN-UP STANDARD

The groundwater clean-up criteria for Sites SS-06 and SS-08 were based on Michigan Response Division Operational Memorandum #8, Revision 4 (6/8/95) listed in the RAP/DD for Site SS-08 (ICF, 1997A). The generic industrial criteria and generic residential criteria are identical in groundwater for the compounds of concern at this site. The criteria for benzene, ethylbenzene, and xylenes are 5, 74, and 280, respectively (ICF, 1997A). The benzene criteria is health based, the ethylbenzene and xylenes criteria are the aesthetic criteria which are lower than the health-based criteria.

CURRENT INVESTIGATION

AmTech conducted pilot tests at Sites SS-06 and SS-08 as the next step toward the full scale implementation of the AS and SVE systems. The objectives of the pilot testing described in this report were to establish the design parameters for full scale implementation of AS/SVE at Sites SS-06 and SS-08, and determine if soil vapor extraction will be needed to remove vapors generated by the AS systems.

The objectives were met by conducting pilot tests at three sites. SVE pilot tests were conducted at SS-06, SS-08 Location A and SS-08 Location B. AS pilot tests were conducted at SS-06 and SS-08 Location B.

Sealed multilevel monitoring wells were used to collect data on the effectiveness of the two technologies at the test sites. The effectiveness of SVE was determined based on vacuum results from transient and steady state tests. The volatile loading for the SVE systems was determined for periods of two weeks of operation at Site SS-06 and 11 days of operation at SS-08 Location B. Air sparging effectiveness was determined based on the presence of conservative tracers at monitoring wells (helium and sulfur hexafluoride), increases in

dissolved oxygen (DO) and oxidation reduction potential (ORP), volatiles production from sparging, and the presence of helium in vadose zone monitoring wells.

RESULTS OF PILOT TEST INVESTIGATIONS

Air sparging was determined to be effective at both test sites. The recommended AS well spacing was 60 feet and 50 feet for sites SS-06 and SS-08 respectively. The design net flow rate per sparge well is 11 scfm at 14 psi (at the wellhead) with a 50 percent pulse cycle. Design screen interval for the sparge wells is 20 - 22 feet below the seasonal average water table at both sites. The vapor load at Site SS-06 will be significant. Air sparging at this site without vapor collection will not be possible. At Site SS-08 air sparging without vapor collection could not be evaluated due to the lack of volatile contamination in groundwater at the test site ("hot spot 3"). However, it is recommended that SVE be implemented with AS at SS-08 due to the potential for build-up of explosive vapors beneath buildings and the tarmac.

SVE was determined to be effective for capture of sparge air at all three sites. The recommended SVE well spacing is 120 and 100 feet, respectively for sites SS-06, and SS-08. The recommended flow rates per well are 300 scfm for all areas of Site SS-06, and all areas of Site SS-08 that do not have surface cover. For areas of SS-08 with surface cover, a design flow rate of 250 scfm is recommended. The recommended SVE vacuum at the wellhead at each site is 50 inches of water column. The spacing and flow rates for the vapor extraction wells can be further optimized as a part of the design process using a numerical model.

1.0 BACKGROUND

1.1 INTRODUCTION

As a result of previous investigations at the now closed Wurtsmith Air Force Base (WAFB), soil and groundwater contamination by volatile and semivolatile organic compounds and lead have been delineated. The current step in the overall plan leading to final restoration is a pilot-scale evaluation of the recommended remedy presented in the Remedial Action Plan (RAP)/Decision Documents (RAP/DD) written for Sites SS-06 (ICF, 1996) and SS-08 (ICF, 1997A). The pilot scale evaluation will be followed by design and full-scale implementation. The cleanup remedy recommended in the RAP/DD for both sites was *in-situ* air sparging (AS) with soil vapor extraction (SVE) and natural attenuation.

This report describes the methods and results of the pilot scale evaluations of AS/SVE application for those portions of sites SS-06 and SS-08 that were identified in the RAP/DD for application of this technology. The scope of the work was performed as proposed in the project workplan by AmTech Engineering, Inc. (AmTech, 1997). This report has been prepared for the United States Air Force Center for Environmental Excellence (USAFCEE), under prime contract number F41624-94-D-8066/DO-0007 by the AmTech/Metcalf & Eddy (M&E) team. The purpose of this pilot testing, described in this report, was to establish the required design parameters for implementing AS/SVE technology at the identified locations. It is intended that the full-scale SVE and AS systems will reduce groundwater and soil contamination to acceptable clean-up levels. The reduction in concentration of contaminants will be monitored through the continuing investigations and operations.

1.2 SITE DESCRIPTION AND HISTORY

WAFB is located in Iosco County, in northeastern Michigan, in the township of Oscoda. The Base is bordered on the northeast by Van Etten Lake, on the northwest, west, and south by the

Au Sable State Forest, and on the east by the community of Oscoda, Michigan. WAFB is on a relatively flat plain 4.5 miles wide, bounded on the west by 80-foot-high bluffs. Elevations on the Base range from 600 to 645 feet. The Au Sable River, located approximately 0.5 miles south of WAFB, flows into Lake Huron, which is approximately 1.0 miles east of the Base. The Au Sable River is the principal river in the area of WAFB and flows eastward along the southern boundary of the Base and discharges into Lake Huron. Van Etten Creek flows along the eastern side of the Base, connecting Van Etten Lake with the Au Sable River.

The Base was initially established as Camp Skeel in 1924 when the Army Air Service began using the Base as a gunnery range and for winter maneuvers. Beginning in 1942 and continuing through World War II, the Base was used as a support for air crew training and renamed Oscoda Army Air Field. From 1924 to 1945, operations consisted of pilot/technical training, bombing techniques, and aerial gunnery. The aircraft used included Dehavilland biplanes and Curtis P-1s, P-39s, P-40s, and P-47s. Hazardous substance activities are assumed to have included the use of petroleum products and solvents during the operation and maintenance of aircraft, for the fire station and associated fire training, and during the production of hospital medical wastes. Other hazardous substance activities included use during the construction of the sewage disposal plant, maintenance areas, runways, and ordnance storage buildings.

The Base was closed in 1945, then reactivated in 1947 for transient activities under the Continental Air Command. With the creation of the Department of the Air Force, the Base was renamed Oscoda Air Force Base (AFB) in 1948, and hosted units from the Air Defense Command.

A major expansion of the Base began in 1958 to support the Air Force's Strategic Air Command (SAC). Over the next 3 years, SAC moved the 4026th Strategic Wing, the 920th Air Refueling Squadron (AREFS), and the 379th Bombardment Wing (BMW) to the Base. The 379th BMW became the host unit at WAFB in 1961, assimilating personnel and equipment

from the 4026th, which was deactivated. Major tenant units included the 2030th Communications Squadron; Detachment 28, 26th Weather Squadron; Detachment 14, 390th Management Engineering Squadron; Detachment 224, 3753rd Field Training Squadron; and the 71st Flying Training Wing. In 1992, responsibility for these units was transferred to the newly established Air Combat Command (ACC).

From 1948 to 30 June 1993, operations consisted of fighter and bomber training, air-to-ground and air-to-air gunnery training, and refueling operations. The aircraft used included F-86s, F-102s, F-106s, B-52s, and KC-135s. Hazardous substance generation may have been included with expanded uses of petroleum, oil, and lubricant (POL) facilities. The ordnance storage areas were expanded, and the explosive ordnance disposal (EOD) area was introduced. Fire training activities included the construction of aboveground storage tanks (ASTs) and underground storage tanks (USTs), oil/water separators, drums storage areas, the Defense Reutilization and Marketing Office (DRMO) facility, and hazardous waste accumulation points. Also during this time, the various landfills were build and used for disposal of wastes produced on the base.

WAFB became a Base Realignment and Closure (BRAC) II site when it was officially closed on June 30, 1993 (Air Force Base Conversion Agency, 1995). Since that time, various studies and investigations of potential environmental problems and their remediation have been ongoing.

The Base is currently maintained by a caretaker force. WAFB has also been nominated to be placed on the National Priorities List (NPL). If and when the Base is listed, a Federal Facilities agreement will go into effect. The Air Force is committed to effective environmental compliance and stewardship for Air Force lands to maintain access to the air, land, and water needed to maintain and improve Air Force mission capability.

1.3 SURROUNDINGS

WAFB is located in Iosco County in the Northern part of Michigan's Lower Peninsula at approximately 44°18' North and 83°22' West (See Figure 1-1). The Base is bounded on the northeast by Van Etten Lake; to the northwest, west, and south by Au Sable State Forest; and to the east by the community of Oscoda (See Figure 1-2). The Base is less than one mile west of the western shore of Lake Huron. Van Etten Lake is a man-made lake that is surrounded by recreational cottages and dwellings of local residents.

While WAFB was in operation, approximately 8,000 people lived and worked at the Base, with approximately 11,000 people living in adjacent communities. The economic viability of the area depended upon tourism and WAFB. There are approximately 889 on-site workers at the Base, as of November 30, 1996 (Wurtsmith Development Council, 1996). Now that the Base is closed, the population of Oscoda Township is approximately 5,200 (Buchman, 1994).

1.4 SITE GEOLOGY

The geology of the area consists of unconsolidated clastic deposits and underlying bedrock. The bedrock is composed predominantly of clastic sedimentary rocks over 300 million years old. The unconsolidated sediments are the result of continental glaciation that ended about 13 thousand years ago. Figure 1-3 presents a representative cross-section of geologic units beneath WAFB.

Bedrock beneath the WAFB consists of Mississippian sandstone and shale formations which dip structurally to the southwest into the Michigan Basin. The topographic surface of the bedrock dips to the east as a result of glacial erosion during the Pleistocene Epoch. Depth to bedrock can vary from 100 to 250 feet across the Base due to this unconformity. (See Figure 1-4.)

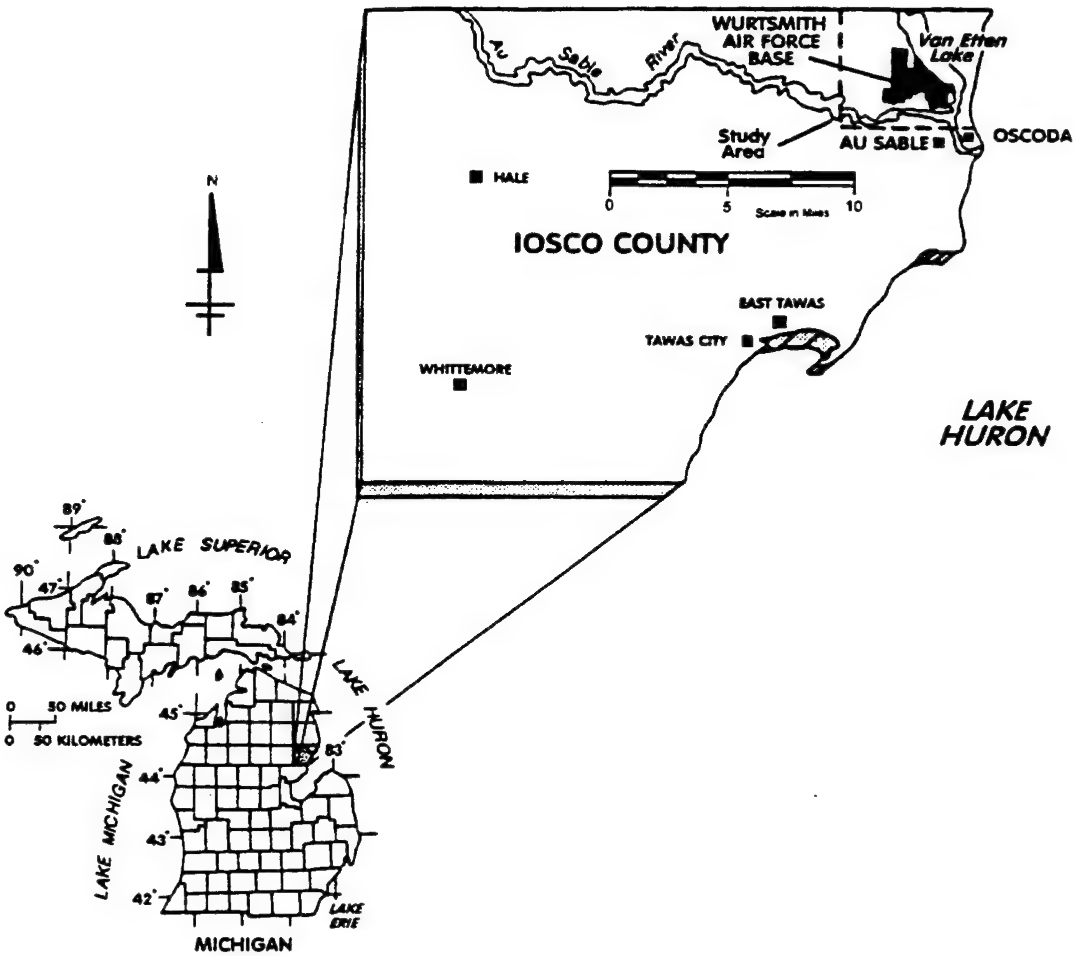


FIGURE 1-1

AmTech
Engineering, Inc.

WURTSMITH AIR FORCE BASE

WURTSMITH AIR FORCE BASE
LOCATION MAP

DATE: 8/28/97	DR.:
F:\DEPT\ENVIR\97033D07	

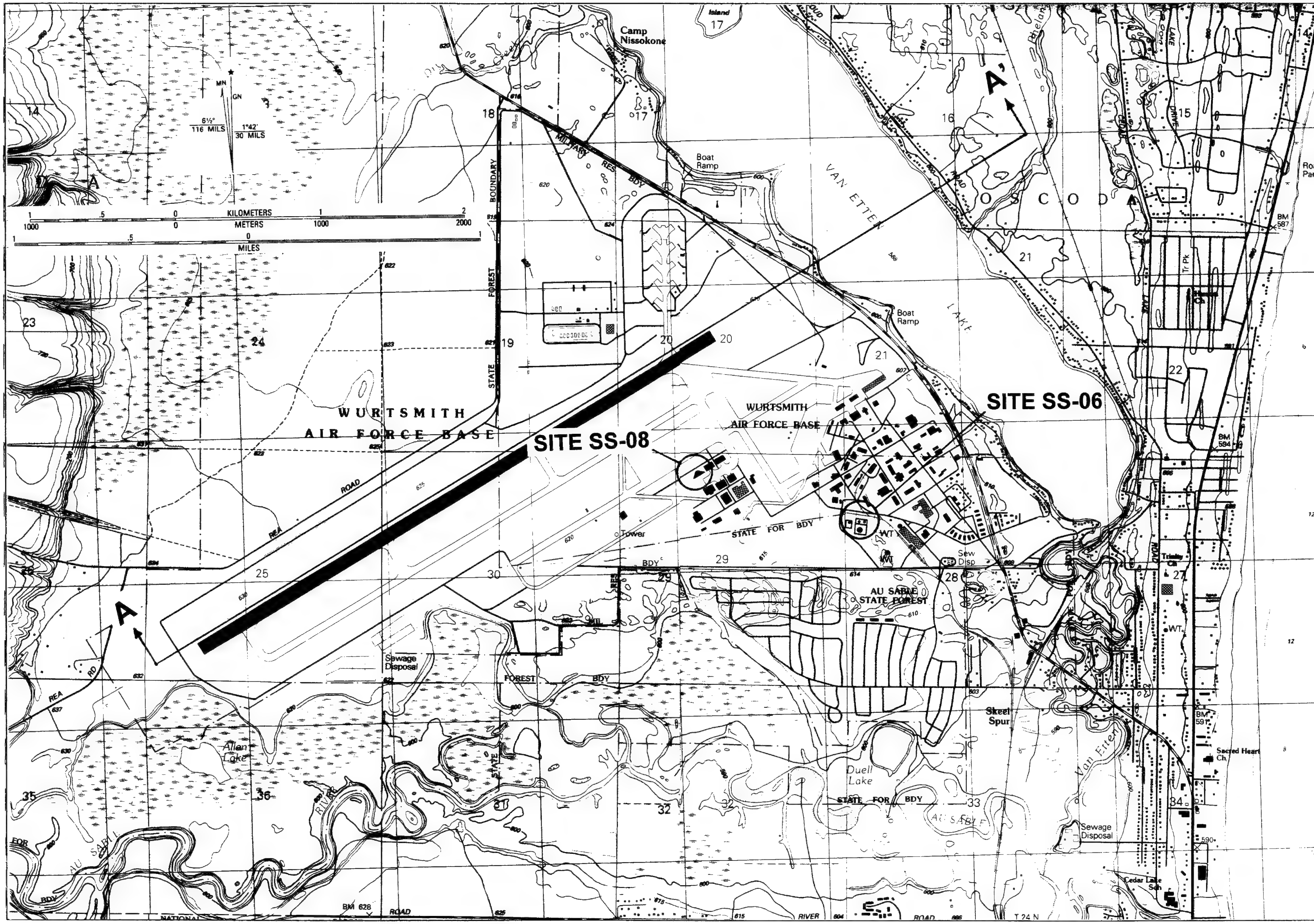


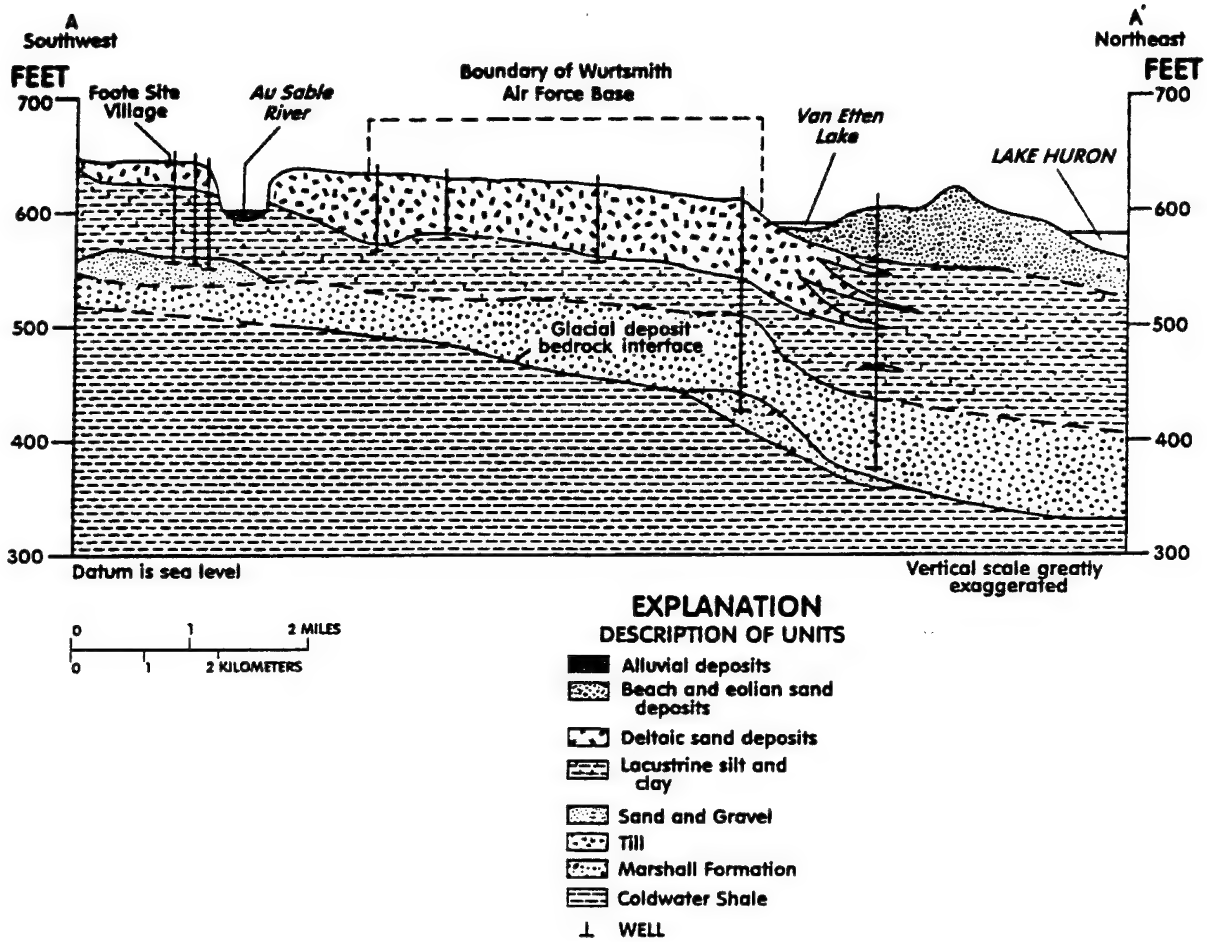
FIGURE 1-2

TOPOGRAPHIC MAP

DATE: 11/3/95 | DR.: G. VENNE

WURTSMITH AIR FORCE BASE

AmTech Engineering, Inc.

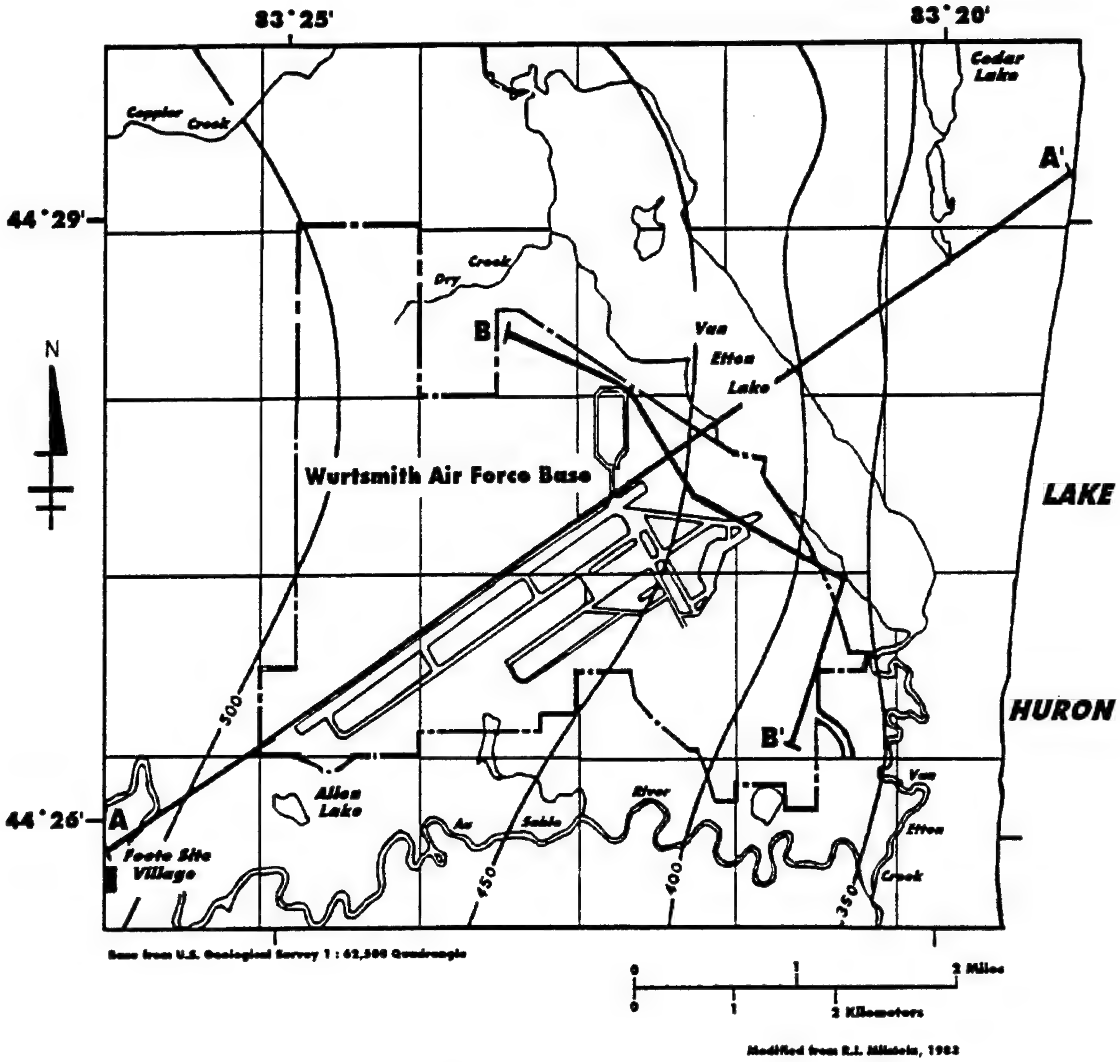


SEE FIGURE 1-2 FOR CROSS SECTION LOCATION

REFERENCE: USGS WATER RESOURCE DIVISION - JAN. 1990

FIGURE 1-3

WURTSMITH AIR FORCE BASE	SITE SS-08	
GEOLOGIC CROSS SECTION A - A'	DATE: 06/15/95	DR.: R. SKERRITT
	SCALE: AS SHOWN	FILE NAME: CROSSAA



EXPLANATION

—500— BEDROCK CONTOUR--Shows elevation of bedrock surface. Contour interval 50 feet. Datum is sea level.

— - — BOUNDARY OF WURTSMITH AIR FORCE BASE

A ——— A' LINE OF GEOLOGIC SECTION

USGS 1990, DRAFT PHASE II - CONFIRMATION/QUANTIFICATION, VOLUME 1 (USAFETAC, 1982)

FIGURE 1-4		
WURTSMITH AIR FORCE BASE	SITE SS-08	
BEDROCK ELEVATION	DATE: 06/14/95	DR.: R. SKERRITT
	SCALE: AS SHOWN	FILENAME: BEDROCK1

The oldest sedimentary bedrock unit beneath the Base is the Coldwater Shale. The Coldwater Shale is primarily a micaceous, blue-gray to green-gray shale. Locally, the weathered upper surface of the shale is reddish and sandy, and can be mistaken for the base of the glacial clays when the Marshall Formation is missing. Thin lenses of limestone, dolomite, sandstone and siltstone are interbedded with the shale, and may represent the transgressive-regressive formation boundary between the Coldwater Shale and the Marshall Formation.

The Marshall Formation lies conformably above the Coldwater Shale, but is only present locally as an outlier (erosional remnant of younger rock above older rock). The Marshall Formation is a very fine to coarse grained sandstone containing layers of shale, sandy shale and siltstone. The sandstone and siltstone are usually gray with the shale being gray to greenish gray. The thickness of the Marshall Formation is generally difficult to determine because the formation is not always present above the Coldwater Shale due to erosion. The Marshall Formation, where present, is estimated to be less than 50 feet thick beneath the Base. Unconsolidated sediments deposited during glacial episodes of the Pleistocene Epoch uncomformably overlie bedrock beneath WAFB. Glacial till and other ice-contact sediments consisting of clay-rich sand, gravel and silt were deposited directly on the bedrock erosional surface. Locally, silty-sand and gravel deposits are found beneath the glacial till. The origin of these sands is unknown, but the greater the degree of sorting suggests a glacial deposit formed by moving water, such as an esker or a kame terrace.

As the glaciers retreated, meltwater flooded the study area, resulting in the formation of the ancestral Great Lakes and their associated lacustrine sediments. Silt and clay sized particles settled out of the lakes to form the extensive silty-clay layer that exists at a depth of 30 to 80 feet beneath the surface. The silty-clay layer is believed to be between 100 to 250 feet in thickness; however, very few wells have actually penetrated the entire thickness of the clay (USGS, 1990). The 30 to 80 feet of unconsolidated sand and gravel sediments above the silty-clay layer are the result of the Pleistocene Au Sable glacial meltwater channel deposits and

Holocene (present day) sedimentary processes which form beach deposits, eolian deposits (sand dunes), and alluvial deposits (Au Sable River and Van Etten Creek).

1.5 HYDROGEOLOGY

Figure 1-3 is a geologic cross section showing the regional geology. The aquifer, discussed in this report, is present in the deltaic sand deposits extending between the Au Sable River and Van Etten Lake (Figure 1-3). The silty-clay aquitard beneath the unconsolidated sediments of the water table aquifer retards downward migration of the contaminated groundwater plumes. Hydrogeologic units below the silty-clay aquitard have been found to be undesirable as a public water supply because of the high dissolved solids or high chloride concentrations (Cummings and Twenter, 1986).

1.5.1 Regional Hydrogeology

The sand and gravel water table aquifer is present across the entire base, with an average thickness of approximately 65 feet and an average saturated thickness of 45 feet. The aquifer consists of brown to gray, medium- to coarse-grained sand containing some gravel lenses. Grain size sieve analyses have shown that, in approximately 80 percent of the samples, the average grain size is in the medium grain range, 0.25 to 0.5 millimeters (Stark *et al.*, 1983). Most of the soils are moderately well sorted. This aquifer was the principal water supply source for WAFB.

The sand and gravel water table aquifer is underlain by a thick confining layer of silty clay. The silty clay aquitard is composed of silt and clay in the upper part, but contains some clay-rich sand and gravel (glacial till) in the lower part. The aquitard can be at least 125 feet thick in areas east and north of Van Etten Lake, and locally as thick as 250 feet. Only one well on base (GST-3) has penetrated the entire silty clay aquitard and it found the clay to be 95 feet thick (Cummings and Twenter, 1986). The silty-clay aquitard effectively isolates the sand and gravel water table

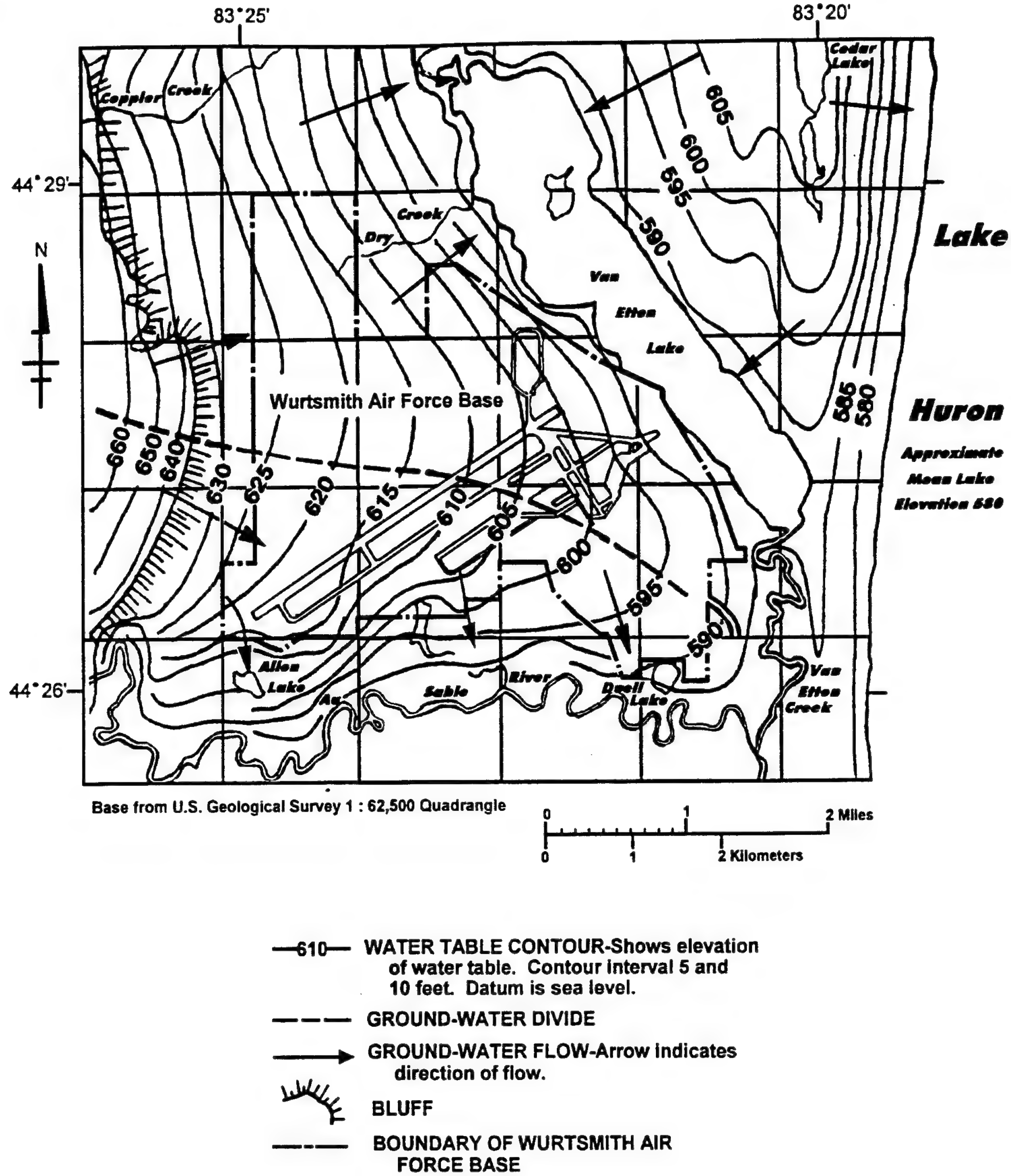
aquifer and restricts vertical migration of groundwater between the sand and gravel aquifer and the hydrogeologic units below (USGS, 1990).

Water table elevations range from approximately 580 feet near Lake Huron to approximately 730 feet in the highlands area west of the base. Water table elevations fluctuate from 1 to 3 feet annually, depending on precipitation (USGS, 1990). A groundwater divide runs diagonally across the base from northwest to southeast. South of the divide, groundwater flows toward the Au Sable River, and north of the divide, toward Van Etten Creek and Van Etten Lake. Eventually, all water from WAFB reaches Lake Huron. The regional groundwater flow regime is not significantly altered by base extraction and supply pumping wells. Figure 1-5 (ICF, 1997B) is a potentiometric map of the region surrounding Wurtsmith AFB, with the groundwater divide identified.

Groundwater use on the base has been drastically reduced since base closure in 1993. Pumping wells AF30 and AF31 located in the east-central part of the base, are pumped intermittently to provide the base water supply. Regional groundwater use is limited due to the sparsely populated State and National Forest lands surrounding the base. Municipal water supply wells for the communities of Oscoda and Au Sable are located approximately 2 miles hydrologically upgradient of the base. Because the base and residents along the Van Etten Lake have access to the Oscoda Municipal System, future use of the water table aquifer as a water source is unlikely.

1.5.2 Site Hydrogeology

The hydrogeology for Sites SS-06 and SS-08 is similar to the regional description presented above. The unconfined water table aquifer and the silty-clay aquitard are the principle hydrogeologic zones of interest in this study. Previous investigations have shown that the unconsolidated aquifer is the only hydrogeologic zone that has been significantly affected by surficial contaminant spills (Cummings and Twenter, 1986). Figure 1-6 is a groundwater flow model for the base that was developed by ICF (1996). Figure 1-6 shows the groundwater



REFERENCE: USGS WATER RESOURCE DIVISION - JAN. 1990

FIGURE 1-5		
WURTSMITH AIR FORCE BASE	SITES SS-08	
GROUNDWATER FLOW	DATE: 9/21/96	DR.: R. SKERRITT
	SCALE: AS SHOWN	FILE NAME: GRDWTR

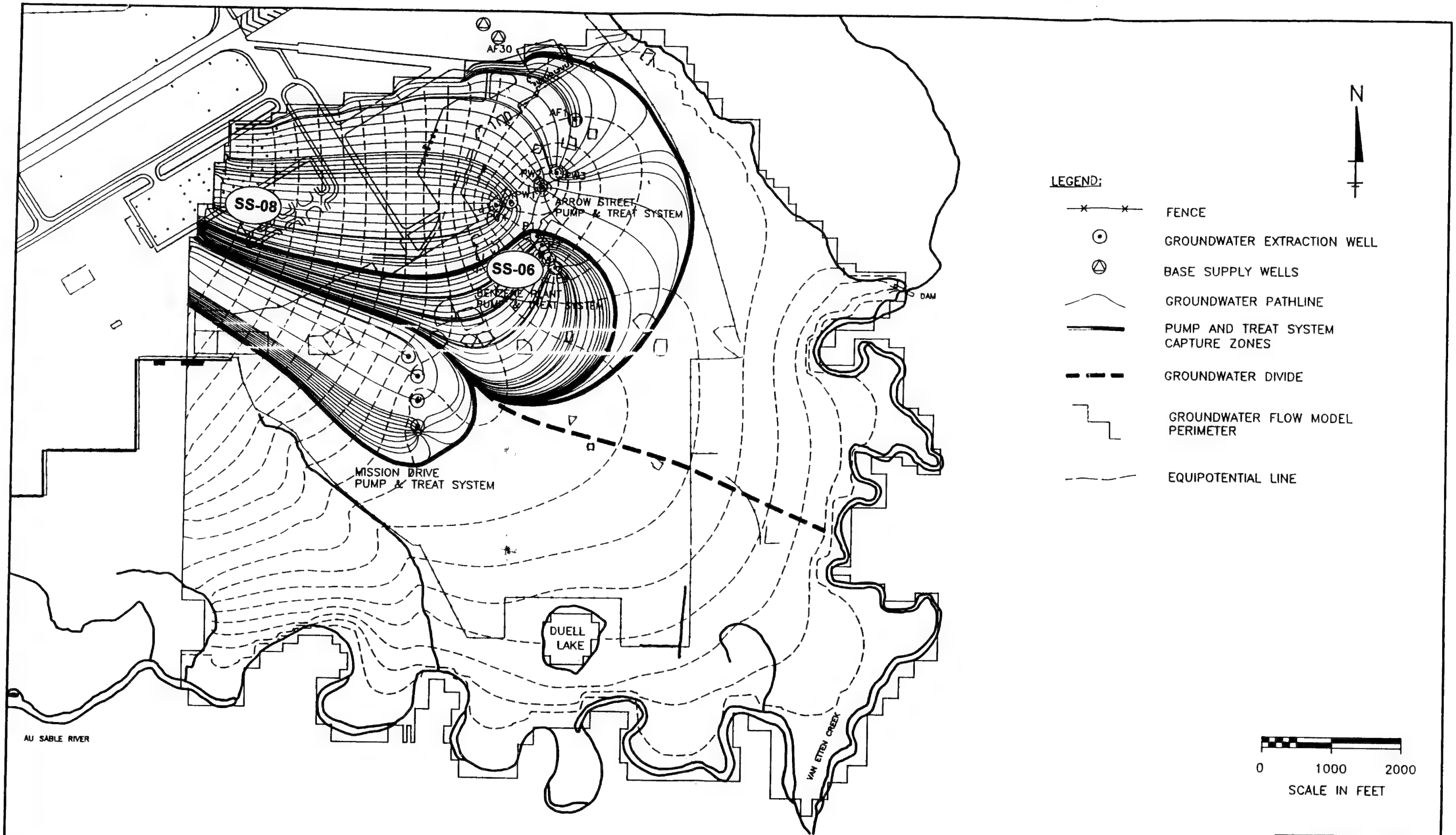


FIGURE 1-6

WURTSMITH AIR FORCE BASE	SS–08
SIMULATED GROUNDWATER PATHWAYS AND CAPTURE ZONE	DATE: 03/30/95 — DR.: D.M.
	SCALE: AS SHOWN — FILE NAME: TTREMB01

flowpaths that approach the three pump and treat groundwater remediation systems at the base. The locations of the areas of SS-06 and SS-08 that are addressed in this pilot study are noted on Figure 1-6.

Site SS-08 groundwater monitoring wells are screened at varying depth intervals, ranging between 15 and 70 feet bgs. Groundwater west of Building 5066 is captured by the Mission Drive Pump and Treat System. The remainder of Site SS-08 groundwater is captured by the Arrow Street and Benzene Plant pump and treat systems. Groundwater in the hot spot areas of SS-08 that are addressed in this investigation, varies in depth between approximately 15 feet bgs. to 12 feet bgs.

The ICF model (Figure 1-6) indicates groundwater flow at Site SS-06 is controlled locally by the Benzene Plant Pump and Treat System. The area of SS-06 being addressed by the AS/SVE remediation is captured by the Benzene Plant Pump and Treat System, according to the ICF model (ICF, 1996). Pre-pump flow in this aquifer was generally east-southeast across the site. The groundwater depth at Site SS-06 is in the range of 20 to 22 feet bgs..

1.6 PROJECT BACKGROUND

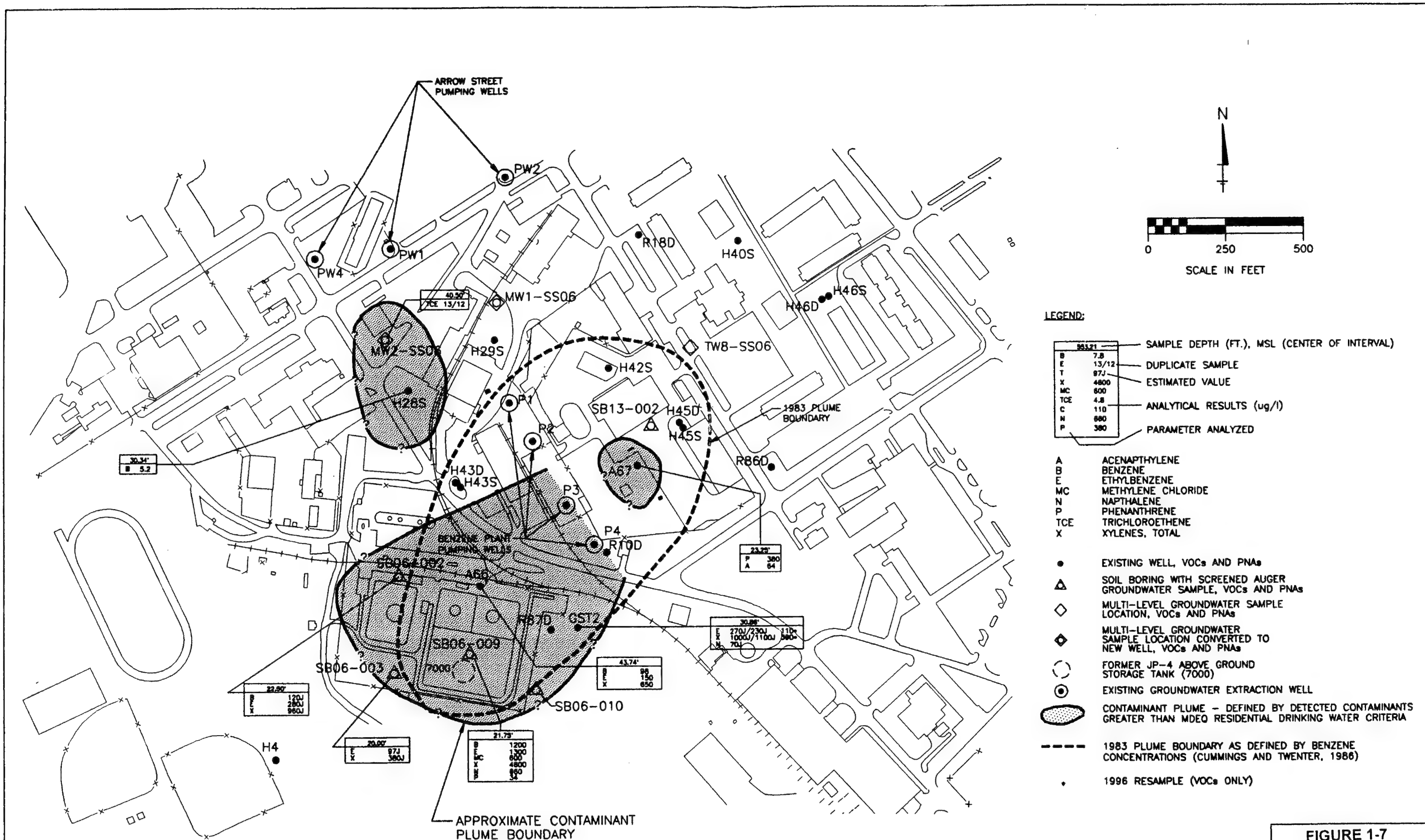
Groundwater and soil investigations have been ongoing at sites SS-06 and SS-08 since the early 1980's. This work culminated in the FS and RAP/DD produced for these sites by ICF in 1996 and 1997. Summaries of the previous investigations at sites SS-06 and SS-08 are provided below followed by a summary of the remedial actions proposed for these sites by ICF.

1.6.1 Site SS-06 Previous Investigations Summary

Site SS-06 comprises the four former and/or existing above ground storage tanks at the Petroleum, Oils, and Lubricants Bulk Storage Facility (POL). No significant fuel spills have been reported at the POL Bulk Storage Facility; however, Tank 7000, a 1.2-million-gallon

above-ground storage tank for JP-4 has leaked in the past. In 1979, a USGS investigation of WAFB found benzene, toluene, and organic compounds in groundwater (Cummings, 1986). In 1983, when free-phase light nonaqueous phase liquids (LNAPL) were discovered near the POL Bulk Storage Facility, a groundwater investigation was initiated by the USGS. Eight deep and four shallow monitoring wells were installed at Site SS-06 to sample groundwater and assess the limits of groundwater contamination. Soil contamination at the facility was never investigated because entry to the tank area was restricted by ongoing operations supporting the base mission. The source of the JP-4 release was believed to have been Tank 7000 which was repaired and returned to operation. The 1983 investigation report (USGS, 1983) concluded that the Arrow Street pump and treat system, installed approximately 1,500 feet north of the POL Bulk Storage Facility in December 1981, was drawing the groundwater plume northward. Figure 1-7 (ICF, 1996) shows the estimated plume boundary as defined by benzene concentrations in the USGS study (Cummings, 1986). The 1983 investigation report recommended the installation of four recovery wells to prevent further migration of the benzene plume and to avoid interference with the Arrow Street TCE removal system. The Benzene Plant pump-and-treat system, installed in December 1991 as an interim remedial action and made operational in January 1992, was designed to remediate groundwater in the POL Area. The plant is currently in operation and consists of four purge wells, two air-stripper towers, thermal off-gas treatment and a free-phase LNAPL recovery system which was installed after the plant became operational. Base personnel have monitored benzene, ethylbenzene, toluene, and total xylene (BTEX) in the influent stream. The trend for these contaminants is that of a slight decrease in concentration over the period of operation of the plant.

In 1994 ICF conducted a remedial investigation of the POL area. A soil gas investigation was conducted in the area of Sites SS-06 and ST-40 to assess the extent of JP-4 contamination in the soil. The soil gas survey detected VOCs and SVOCs. Soil borings located based on the soil gas results detected significant amounts of xylene and naphthalene in the soil in the vicinity of



GROUNDWATER ELEVATIONS - AUGUST 1994

FIGURE 1-7

WURTSMITH AIR FORCE BASE	SITE SS-06		
GROUNDWATER SAMPLE LOCATIONS AND EXCEEDENCES	DATE: 02-20-96	DR.: BRENT	
	SCALE: AS SHOWN	FILE NAME: G3RAPB01	

Tank 7000. Groundwater sampling detected a groundwater plume located approximately between Tank 7000 and the Benzene Plant system and consisting primarily of benzene, ethylbenzene, and xylene. the conclusions of this investigation was that Tank 7000 was the source of the LNAPL and groundwater plume (ICF, 1997B).

ICF measured groundwater elevations and apparent LNAPL thickness during August 22-23, 1994 and August 31- September 1, 1994 (ICF 1997B). Measurable free-phase LNAPL was found in wells H191S, H192S, H193S, H194S, H195S, H197S, and GST2 not far from the recovery wells. Base personnel reported, however that, for the most part, the free-phase LNAPL recovery system was no longer recovering LNAPL. In May 1995 apparent free-phase LNAPL thickness measured in a number of wells located within the POL Area ranged from 0.5 to 2.0 feet thick. Successive attempts to measure free-phase LNAPL in the same wells from June 1995 through November 1995 produced little or no measurable free-phase LNAPL, however.

A ground penetrating radar (GPR) investigation was conducted in the vicinity of Sites SS-06, ST-40, and SS-13 in early January 1996 in an attempt to detect the LNAPL plume and map its lateral extent (ICF 1997B). Appendix A of the Draft FS for Sites SS-06, ST-40, SS-13 and ST-46 presents a detailed description of the GPR investigation.

GPR records were inspected for areas that exhibit decreased signal amplitudes or lower amplitude reflections (anomalous zones). The anomalous zones were plotted on the base map along with each GPR traverse and the interpreted zones of LNAPL is located between the Benzene Plant pump and treat system wells and Tank 7000. Only one anomalous area (strand) occurs northeast or the pump and treat system. That anomalous strand appears to generally coincide with the groundwater divide located between the Benzene Plant and Arrow Street pump and treat systems. The GPR survey was confirmed by soil samples tested with a TPH field kit. Three soil samples and one free-phase LNAPL sample from a skimmer placed in a monitoring well were analyzed for VOCs and SVOCs.

A good correlation exists between the GPR data and the confirmatory samples. In general, samples obtained within the anomalous area (large area and strand) yielded TPH concentrations from 1,000 to 28,000 mg/kg. Most of the samples in the main anomaly were several thousand mg/kg. Outside of the anomalous zones TPH concentrations were significantly lower. They generally were less than 70 mg/kg. Samples obtained from the edge of the interpreted LNAPL zone indicated various concentrations.

As discussed in Appendix A of the Draft FS (ICF, 1997B), calculations were performed to assess the amount of free-versus-residual phase LNAPL remaining at the POL Area. It was determined that the majority of the remaining LNAPL at the site is residual. This is consistent with field observations which show little measurable free-phase LNAPL in the wells within the POL Area.

A soil gas survey and bioventing pilot test were completed by Parsons Engineering Science, Inc. (Parsons ES) in July 1996 in the POL. The study area included a portion of Site SS-06 and site ST-40 within and immediately around the diked above ground storage tank area which included tank 7000 (Figure 1-7). The purpose of the study was to obtain design parameters for full scale implementation of bioventing at this site, as called for in the RAP/DD (ICF, 1997A).

The soil gas study by Parsons ES found soil gas with depleted concentrations of oxygen (below 3 percent), elevated carbon dioxide concentrations (above 5 percent), and total volatile hydrocarbon (TVH) concentrations exceeding 2,000 ppmv in all sampling locations within the bermed POL area and locations immediately north and east of the bermed areas (Parsons ES, 1996).

The results of the bioventing pilot test indicated a moderate oxygen utilization rate ranging from 0.08 percent per hour to 0.45 percent per hour for the tested soils (Parsons ES, 1996). An average soil permeability of 16 darcys was calculated for the vadose zone soils in the POL

area, and a radius of pressure influence of 100 feet was measured for soils 12 to 18 feet below ground surface (bgs.) (Parsons ES, 1996). The rate of hydrocarbon degradation was estimated at 400 to 2,500 milligrams of fuel per kilogram of soil.

The study by Parsons ES indicated that bioventing was feasible for the site and a full scale implementation of the bioventing system was completed in August 1996 (Parsons ES, 1996). A total of eight air injection wells were included in the full scale installation. The injection rate per well varied between 7 and 27 scfm at pressures varying from 1.2 inches of water column to 5.7 inches of water column. The total air injection rate was approximately 125 scfm (Parsons ES, 1996)

1.6.2 Site SS-06 Clean-up Criteria

Future use of the POL area has been classified as industrial by the Final Environmental Impact Statement (EIS) (USAF, 1993). However, the FS and RAP/DD indicated that it was in the owner's best interest that the site be closed with as few restrictions as possible (ICF, 1997B; ICF, 1996). Therefore, residential criteria were used as the final cleanup criteria so that the site could be closed without land use restrictions.

The groundwater clean-up criteria were based on Michigan Response Division Operational Memorandum #8, Revision 4 (6/8/95) listed in the FS (ICF, 1997B). The generic industrial criteria and generic residential criteria are identical in groundwater for the compounds of concern at this site, as provided in detail in the FS report (ICF, 1997B). The criteria for benzene, ethylbenzene, and xylenes are 5, 74, and 280, respectively (ICF, 1997B). The benzene criteria is health based, the ethylbenzene and xylenes criteria are the aesthetic criteria which are lower than the health-based criteria.

1.6.3 RAP/DD Preferred Remedial Alternative for SS-06

The RAP/DD (ICF, 1996) proposed AS/SVE as the preferred alternative for remediating the residual LNAPL contamination in groundwater and soils at the water table in the area between the Parsons ES bioventing system and the Benzene Plant Pump and Treat System recovery wells. Figure 1-8 shows the proposed location of the AS/SVE system, the extent of treatment for the bioventing system, and a proposed layout for the AS/SVE system. The RAD/DD proposed AS/SVE within the area of LNAPL exceeding 5,000 mg/kg and SVE only in the area where LNAPL was estimated to be between 2,000 and 5,000 mg/kg.

The RAP/DD (ICF, 1996) also proposed an AS/SVE curtain through a portion of the POL area outside of the estimated extent of the groundwater plume (Figure 1-8). The AS/SVE curtain was removed from consideration during the AFCEE review process for the RAP/DD. The RAP/DD assumed SVE well spacing was 50 feet and the assumed AS well spacing was 25 feet.

1.6.4 Site SS-08 Previous Investigations Summary

From 1979 to 1981, the United Stated Geological Survey (USGS) did a preliminary groundwater study at Site SS-08. Trichloroethene (TCE), dichloroethylene (DCE) and benzene were each detected in the groundwater samples which were collected (USGS, 1983).

In September 1988, a leaking fuel line was found at hydrant 22A adjacent to Parking Spot # 19 during a pressure check of the fuel system under the SAC Operational Apron (see Figure 1-9 for locations). In October 1988, contaminated soil was excavated from the area around the leaking fuel line fitting, and the Michigan Department of Environmental Quality (MDEQ) collected groundwater samples at the site. The analysis of these samples showed concentrations of benzene, toluene, ethylbenzene, and xylenes (BTEX) that confirmed impact to the groundwater.

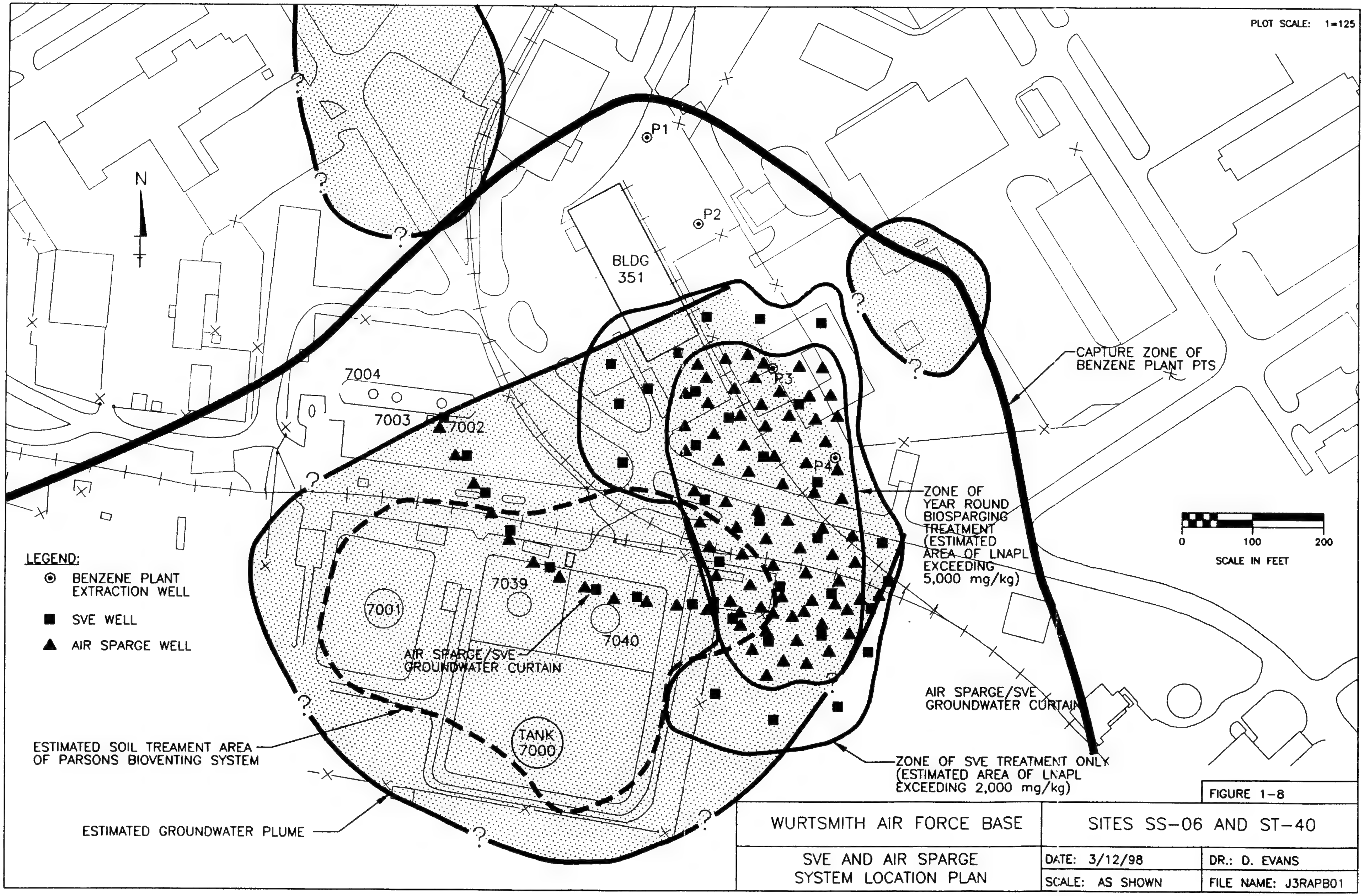


		FIGURE 1-8
WURTSMITH AIR FORCE BASE	SITES SS-06 AND ST-40	
SVE AND AIR SPARGE SYSTEM LOCATION PLAN	DATE: 3/12/98	DR.: D. EVANS
	SCALE: AS SHOWN	FILE NAME: J3RAPB01

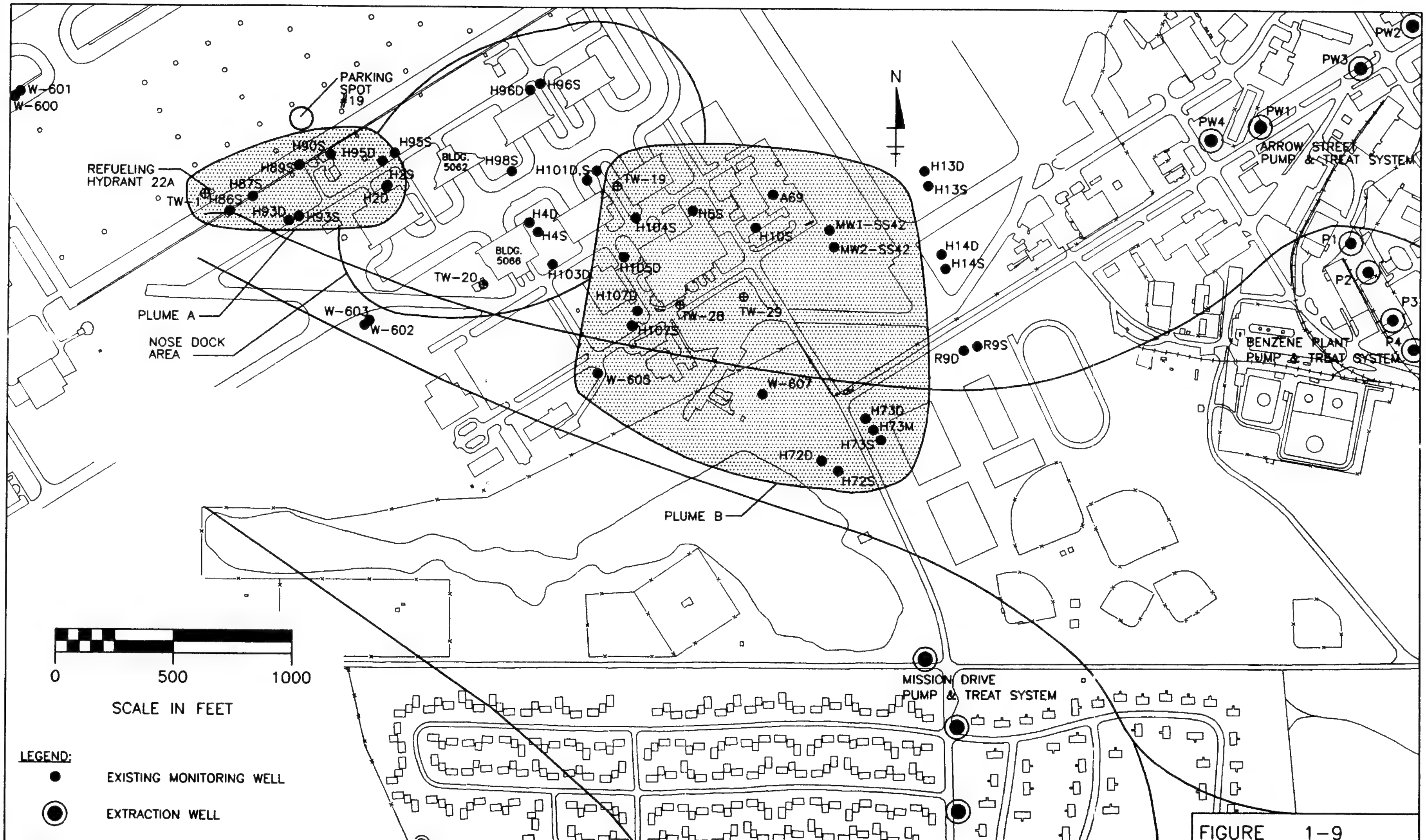


FIGURE 1-9		
WURTSMITH AIR FORCE BASE	SITE SS-08 LOCATION	
GROUNDWATER PLUMES A AND B	DATE: 3/12/98	DR.: EM
	SCALE: AS SHOWN	FILE NAME: JRAPA01

In 1990, the USGS conducted a groundwater study adjacent to and downgradient of the SAC Operational Apron. BTEX contamination was detected (WWES, 1994). This reference is used because this USGS information was found in the WWES report. The WWES report, however, did not reference where the USGS information was obtained.

During 1992 and 1993, WW Engineering and Science (WWES) conducted a remedial investigation of Parking Spot #19. During their investigation, soil and groundwater samples were collected from the SAC Operational Apron and Parking Spot #19 and Nose Dock areas of Site SS-08 (WWES, 1994). Soil samples were analyzed for BTEX and PNAs, and groundwater samples were analyzed for BTEX and PNAs, and purgeable hydrocarbons. Based on the results of the RI, soils at Parking Spot #19 are not impacted above MDEQ generic residential and industrial cleanup criteria with either BTEX or PNA compounds. Groundwater samples were found to contain BTEX, TCE, DCE and PNAs.

Groundwater samples collected from monitoring wells H90S and H87S, which are located further downgradient and cross gradient of the predicted Parking Spot #19 plume, were found to be contaminated with BTEX compounds. WWES concluded that these detections were possibly a result of additional sources from the Nose Dock area and SAC Operational Apron (WWES, 1994). It appears that the natural groundwater gradient and the operation of the Arrow Street and Mission Drive treatment plants have affected the direction and extent of groundwater contamination at the site.

In 1993, WWES conducted a soil gas investigation using Petrex soil gas samplers. The results of the investigation indicated that fuel-related volatile compounds were potentially present under the center portion and western edge of the SAC Operational Apron. The investigation also noted smaller areas of tetrachloroethene (PCE) and TCE contamination in the soil (WWES, 1993).

In January 1995, Wurtsmith caretaker sampling was conducted consisting of groundwater sampling for VOCs. PCE and TCE were detected in only one well (H14S) at concentrations exceeding MDEQ generic industrial cleanup criteria.

In September 1995, Brown and Root Environmental (formerly Haliburton NUS), removed the fuel lines to the south of the Operational Apron and the two 25,000-gallon underground storage tanks (USTs). They then collected soil samples of the surrounding soils, and installed ten temporary monitoring wells in the SAC Operational Apron area and collected groundwater samples. Soil samples were analyzed for VOCs, semivolatile organic compounds (SVOCs), and total lead. Groundwater samples were analyzed for VOCs and SVOCs. Lead was detected in several of the soil samples at concentrations below site-specific background levels. Acetone was detected in several of the groundwater samples at concentrations below generic residential and industrial cleanup criteria. In addition, one well (TW-0476) was found to contain ethylbenzene and xylenes concentrations that exceeded MDEQ generic industrial cleanup criteria.

In 1994 and 1995, ICF conducted a remedial investigation of Site SS-08, which focused on the areas to the south of the SAC Operational Apron, including the hangars and associated oil/water separators (ICF, 1995). The ICF investigation included soil gas, surface and subsurface soil, and groundwater sampling for the analysis of VOCs. No contaminants were detected in any of the surface or subsurface soils at concentrations exceeding MDEQ residential or industrial criteria. There were VOCs detected in some of the groundwater samples that exceeded MDEQ residential and industrial criteria and federal MCLs (ICF, 1995).

1.6.5 Site SS-08 Clean-Up Criteria

Future use of Site SS-08 classified as industrial by the EIS (USAF, 1993). However, the RAP/DD indicated that it was in the owner's best interest that the site be closed with as few

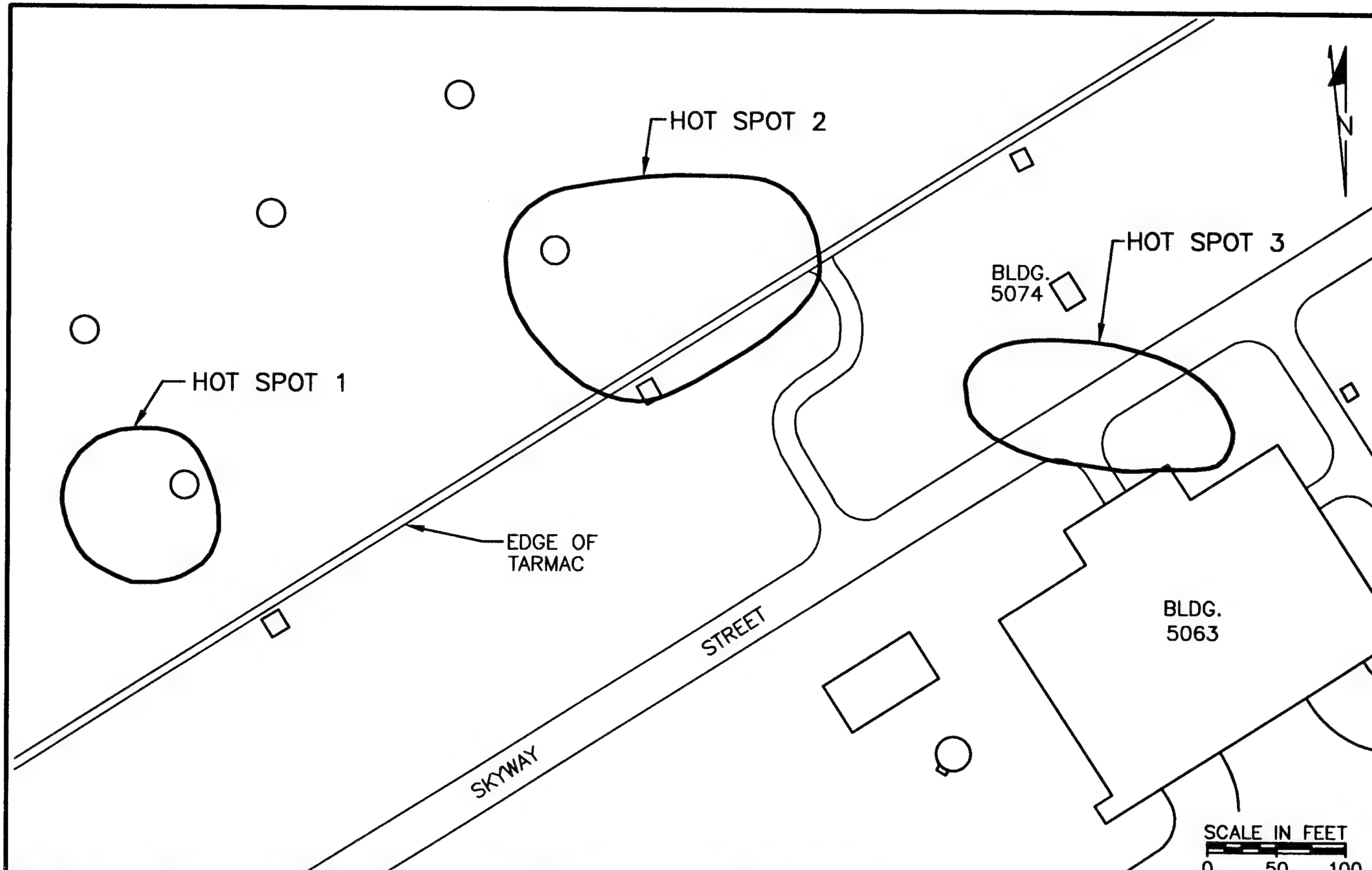
restrictions as possible (ICF, 1997A). Therefore, residential criteria were used as the final cleanup criteria so that the site could be closed without land use restrictions.

The groundwater clean-up criteria were based on Michigan Response Division Operational Memorandum #8, Revision 4 (6/8/95) listed in the RAP/DD (ICF, 1997A). The generic industrial criteria and generic residential criteria are identical in groundwater for the compounds of concern at this site (ICF, 1997A). The criteria for benzene, ethylbenzene, and xylenes are 5, 74, and 280, respectively (ICF, 1997A). The benzene criteria is health based, the ethylbenzene and xylenes criteria are the aesthetic criteria which are lower than the health-based criteria.

1.6.6 RAP/DD Preferred Remedial Alternative for Site SS-08

The RAP/DD (ICF, 1997A) proposed AS/SVE as the preferred alternative for remediating the residual groundwater contamination at Site SS-08. The hot spots designated for remediation within are SS-08 are shown on Figure 1-10. The assumed radius of influence for air sparging wells was 25 feet and the assumed radius of influence for vapor extraction wells was 50 feet (ICF, 1997A). Contaminants were stated to occur to a depth of 15 feet below the water table or approximately 30 feet bgs. (ICF, 1997A).

The RAP/DD (ICF, 1997A) also indicated that confirmatory sampling in the area in and around the hot spots would be necessary to better establish the extent of the hot spots. The first round of confirmatory sampling was completed by AmTech in December 1997, and a second round of sampling is currently planned, based on the results of the first round. Results of this sampling have not yet been reported.



M&E Metcalf & Eddy

WURTSMITH AIR FORCE BASE

SITE SS-08 GROUNDWATER HOT SPOT LOCATIONS

OSCODA, MICHIGAN

Project Number	
021746	
File Name	Figure
21746-8	1-10

1.7 PILOT STUDY OBJECTIVES

The objectives of this pilot study are to provide design specifications for implementation of full scale AS/SVE systems in portions of sites SS-06 and SS-08. The portions of these sites to be addressed were established in the RAP/DD for the two sites (ICF,1996; ICF 1997A) and are shown on Figures 1-9 and 1-10. The design specifications include well spacing for AS and SVE wells for the full scale system and other specifications that will aid in producing an optimal design for the AS/SVE system at each site. The design specifications also include the expected flow rate and vacuum for single SVE wells and the expected pressure and flow rate requirements for single AS wells. The design specifications also include the expected volatile load in the extracted vapor stream.

An additional objective of the pilot testing was to evaluate the feasibility of conducting AS without SVE to collect the soil vapor generated from the sparge system. This was evaluated using an *in situ* respiration test to determine the expected rate of biological degradation and a sparging test without vapor extraction to estimate the rate of volatiles production.

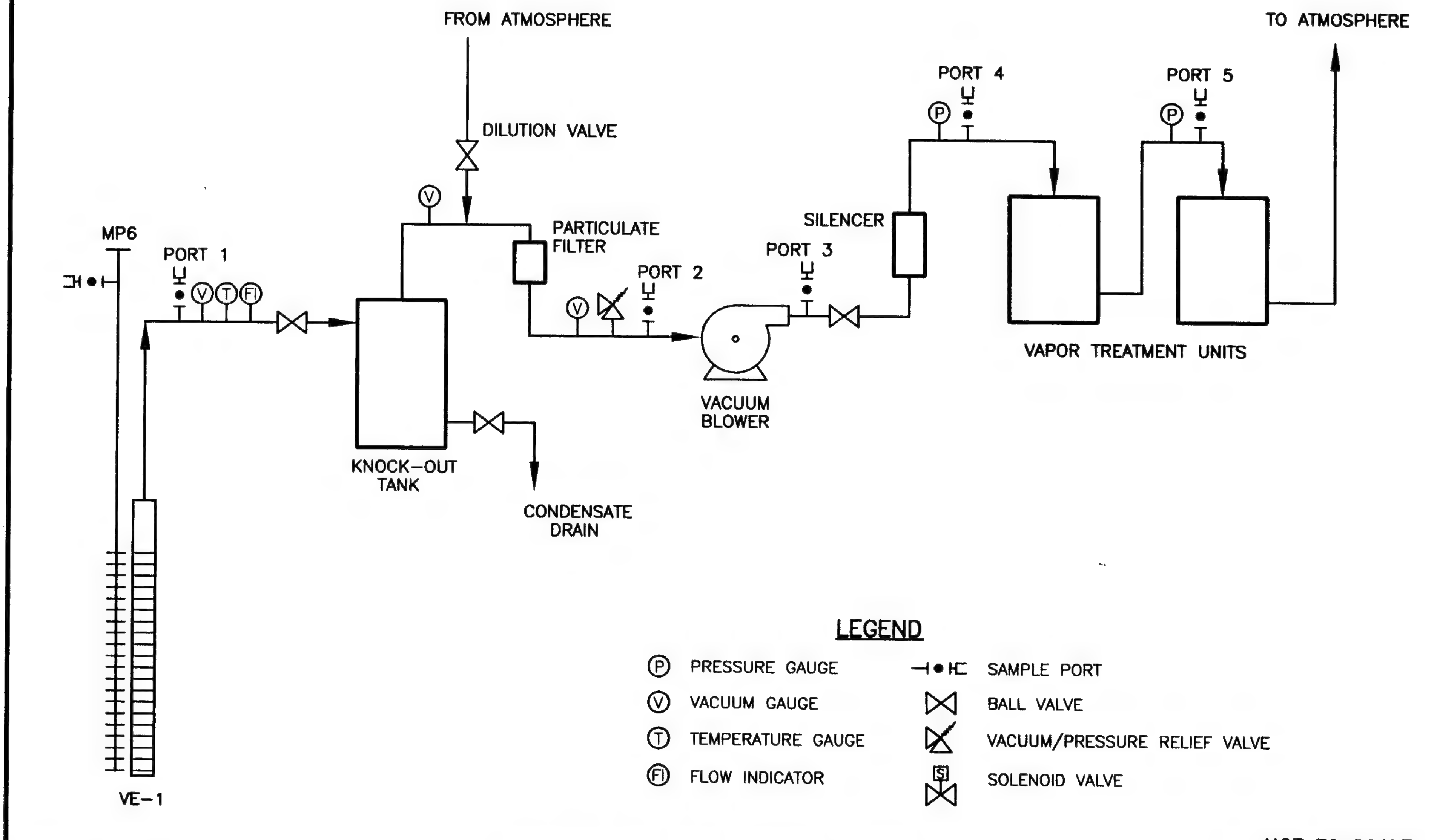
2.0 EQUIPMENT

2.1 SOIL VAPOR EXTRACTION PILOT TEST SYSTEM

A trailer mounted pilot SVE system was used for the vacuum extraction pilot tests. Figure 2-1 is a process and instrumentation diagram (P&ID) for the pilot soil gas extraction system and the soil gas treatment system. A regenerative blower applies a vacuum to the system extracting soil gas from the vadose zone well (VE-1). The vacuum, temperature, and flow rate of the extracted soil gas is established using instrumentation installed between the wellhead and the vacuum system knock-out tank. Soil gas is directed into the knock-out tank where water droplets are removed (and in some cases water vapor is condensed). Soil gas travels from the knock-out tank through a particulate filter to the blower. From the blower the soil gas is directed through a silencer and to the soil gas treatment system.

The soil gas treatment system consists of two parallel trains of two carbon vessels in series. The carbon canisters each contain 175 pounds of carbon designed for gas phase flow. Volatile constituents in the soil gas are removed by the carbon and the treated soil gas is released to the atmosphere.

Ports for sampling and instruments for monitoring the system performance are included as shown on the P&ID. Carbon canister breakthrough is detected in the port between the carbon vessels (in series) and after the second carbon vessel. When breakthrough is detected between the carbon units, the volatile removal efficiency is monitored and the discharge to atmosphere is monitored. When it is determined that the first carbon vessel in the series is no longer removing significant quantities of volatiles, or if breakthrough is detected at the discharge pipe from the second carbon vessel, the first vessel in the series is removed and marked for disposal. The second vessel in series is then moved to the first position and a new carbon vessel is placed as the second vessel.



M&E Metcalf & Eddy

WURTSMITH AIR FORCE BASE

SOIL VAPOR EXTRACTION PILOT UNIT P&ID

OSCODA, MICHIGAN

Project Number	
021746	
File Name	Figure
21746-7	2-1

Photographs of the above SVE system and AS system, well installation and other pertinent information are shown in Appendix G.

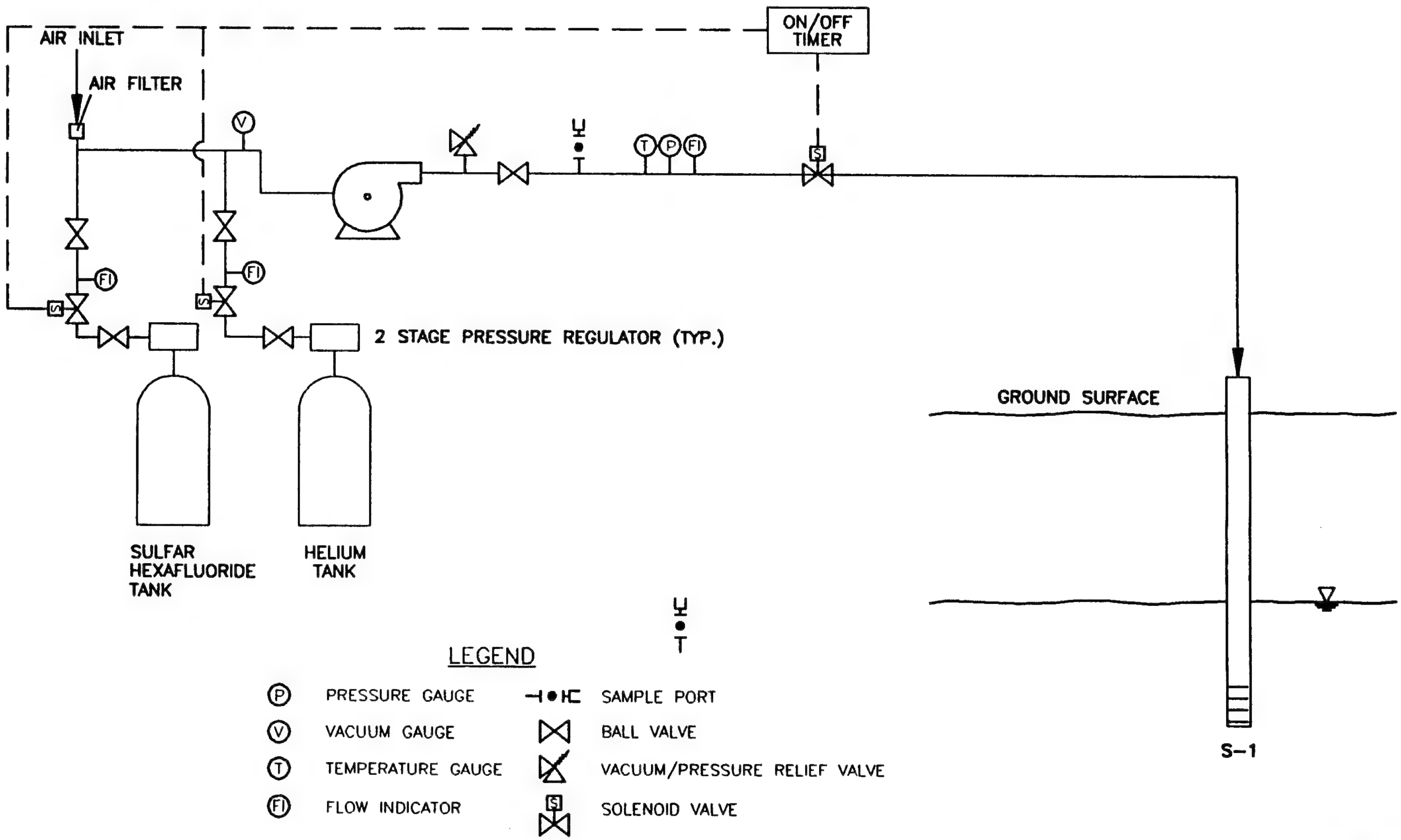
2.2 AIR SPARGING PILOT TEST SYSTEM

A trailer mounted pilot scale air sparging system was used to conduct the AS pilot test. Figure 2-2 is a P&ID for the AS system used for the test. A rotary vane compressor pulls atmospheric air through an air filter and delivers the air at pressures up to 20 psi and flow rates up to 20 scfm to the air sparge system. The pressure in the system is regulated with an adjustable pressure relief valve.

Helium and sulfur hexafluoride tanks are connected to two stage regulators which can deliver these gases at low pressure to the sparge air. The gases travel from the regulator through individual flow meters (calibrated for the specific gases) and are injected into the stream of sparge air between the air filter and the compressor intake. By supplying the gases at this point, it is certain that the gases have mixed well prior to reaching downstream sampling ports where the helium concentration is monitored.

The temperature, pressure, and flow rate of the mixed gas stream is monitored upstream of the air sparge well. The pilot sparge system is connected to the wellhead using flexible pressure hose and cam-lock fittings.

A cycle timer is used to produce pulsed sparging. The timer operates solenoid valves which allow the pulsing. The timer can be set to provide any time interval from continuous sparging to no sparging. The timer cycle is 10 minutes. If the timer dial is set at two, sparge air will be supplied to the well for eight minutes and the sparge well will receive no air for 2 minutes. The cycle repeats every 10 minutes. The timer activates a solenoid valve at the wellhead that opens and discharges air to the atmosphere. While the valve is open insufficient pressure is



NOT TO SCALE

AmTech Engineering, Inc.	WURTSMITH AIR FORCE BASE AIR SPARGING PILOT UNIT P&ID OSCODA, MICHIGAN	Project Number 97033D07	
		File Name 21746-7	Figure 2-2

present to allow flow to the sparge well. When the timer closes the solenoid, the pressure builds back up and sparging starts again. Solenoid valves for the helium and sulfur hexafluoride shut these streams down during the air sparge off cycles to prevent wasting gases. The compressor remains on through sparge-off cycles. This helps to prevent blower wear that can occur with on and off cycles.

2.3 MONITORING EQUIPMENT AND INSTRUMENTATION

Groundwater field parameters measured during the tests included dissolved oxygen (DO), oxidation reduction potential (ORP), pH, specific conductance, salinity, total dissolved solids (TDS), and temperature. A YSI 6000™ flow cell with probes for the above referenced parameters was used for obtaining measurements. Water was pumped from a given monitoring well using a GeoTech™ peristaltic pump, and polyethylene tubing dedicated to each monitoring well. The pump transferred groundwater to the flow cell at a rate of approximately 0.15 gpm. From the flow cell, the water was transferred to a holding tank for disposal.

Soil gas field parameters measured during the tests included oxygen concentration, carbon dioxide concentration, methane concentration, helium concentration, and volatile organics concentration. Oxygen, carbon dioxide, and methane were measured using a LandTech GA90™ gas analyzer. Helium was measured using a Mark™ helium detector. Volatile organics concentration was measured using an OVM™ PID.

Vacuum readings at wells were taken using Dywer digital manometers. Digital manometers for the range of 0 - 20 inches of water column and for the range of 0-200 inches of water column were used. For transient air permeability tests, InSitu™ transducers and 4-channel data logger were used. Barometric pressure readings were also obtained using a barometric transducer and the data logger.

All instruments that could be calibrated were calibrated daily. The helium detector had an internal calibration sequence that occurred automatically approximately every one half hour. The digital manometers were calibrated prior to every reading. The pressure transducers could not be calibrated, but they were checked for accuracy against the digital manometers.

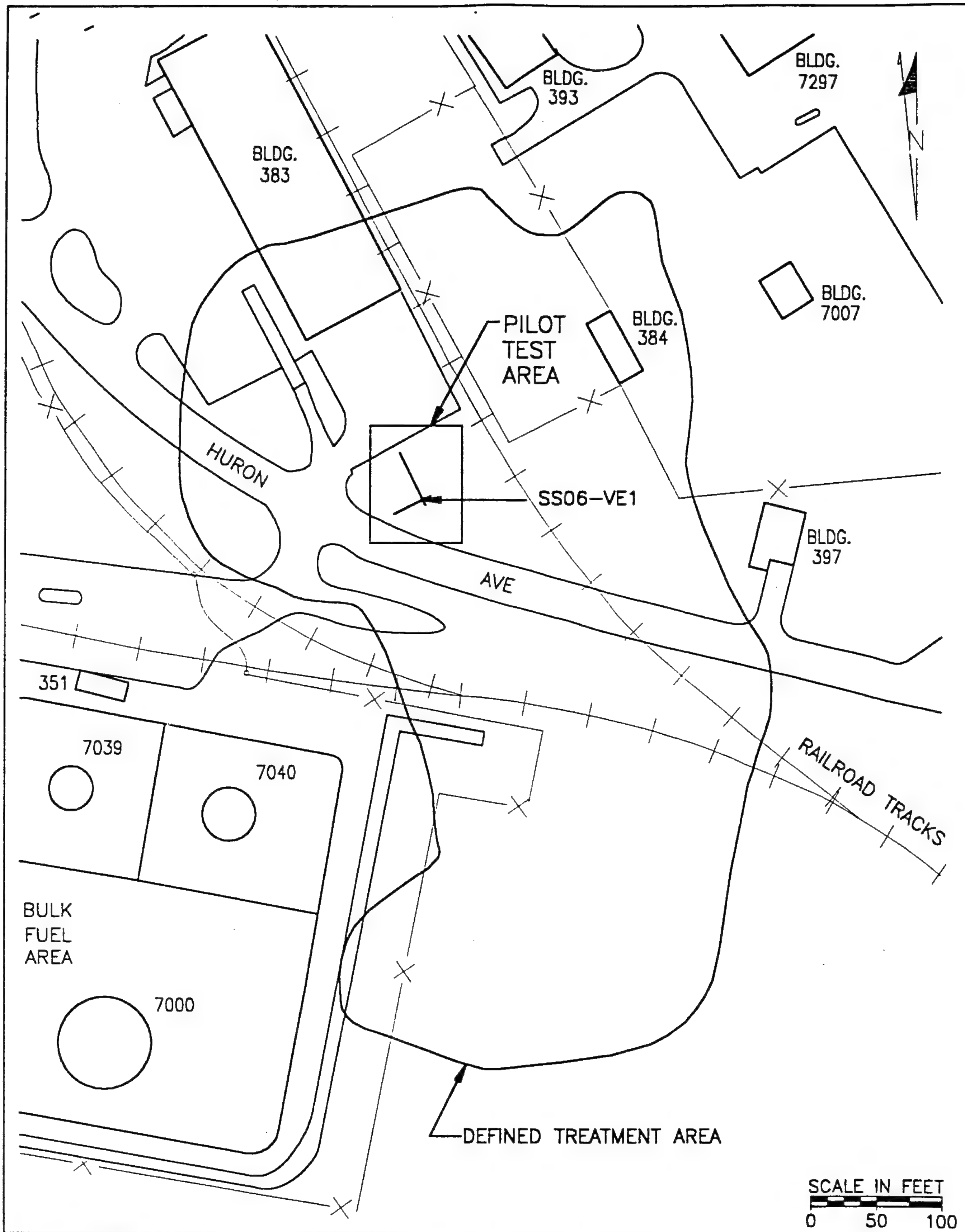
2.4 WELL LAYOUT FOR PILOT TESTS

Figure 2-3 shows the pilot test location within the remediation area at Site SS-06. This location was chosen because of the likelihood of encountering soils that were impacted with residual phase LNAPL, and because the location does not interfere with normal traffic patterns through this area.

The layout of the vacuum extraction well (VE-1), air sparge well (AS-1), and monitoring wells is shown on Figure 2-4. The monitoring wells locations were chosen to provide 360 degree coverage around the vacuum extraction and sparge wells and to provide approximate distances of 5, 10, 15, 25, and 40 feet away from the vacuum extraction and sparge wells.

Figure 2-5 shows the location of the pilot test areas within the groundwater contamination hot spots at Site SS-08. The locations were chosen to be approximately centered within the hot spot areas and to be in locations that would not interfere with activities on the tarmac or building 5063.

The layout of the vacuum extraction well (VE-1), and monitoring wells at Site SS-08 Location A is shown on Figure 2-6. As with Site SS-06, the monitoring wells locations were chosen to provide 360 degree coverage around the vacuum extraction well and to provide approximate distances of 5, 10, 15, 25, and 40 feet away from the vacuum extraction well.



M&E Metcalf & Eddy	WURTSMITH AIR FORCE BASE SITE SS–06 PILOT TEST LOCATION OSCODA, MICHIGAN	Project Number 021746	
		File Name 21746–2	Figure 2-3

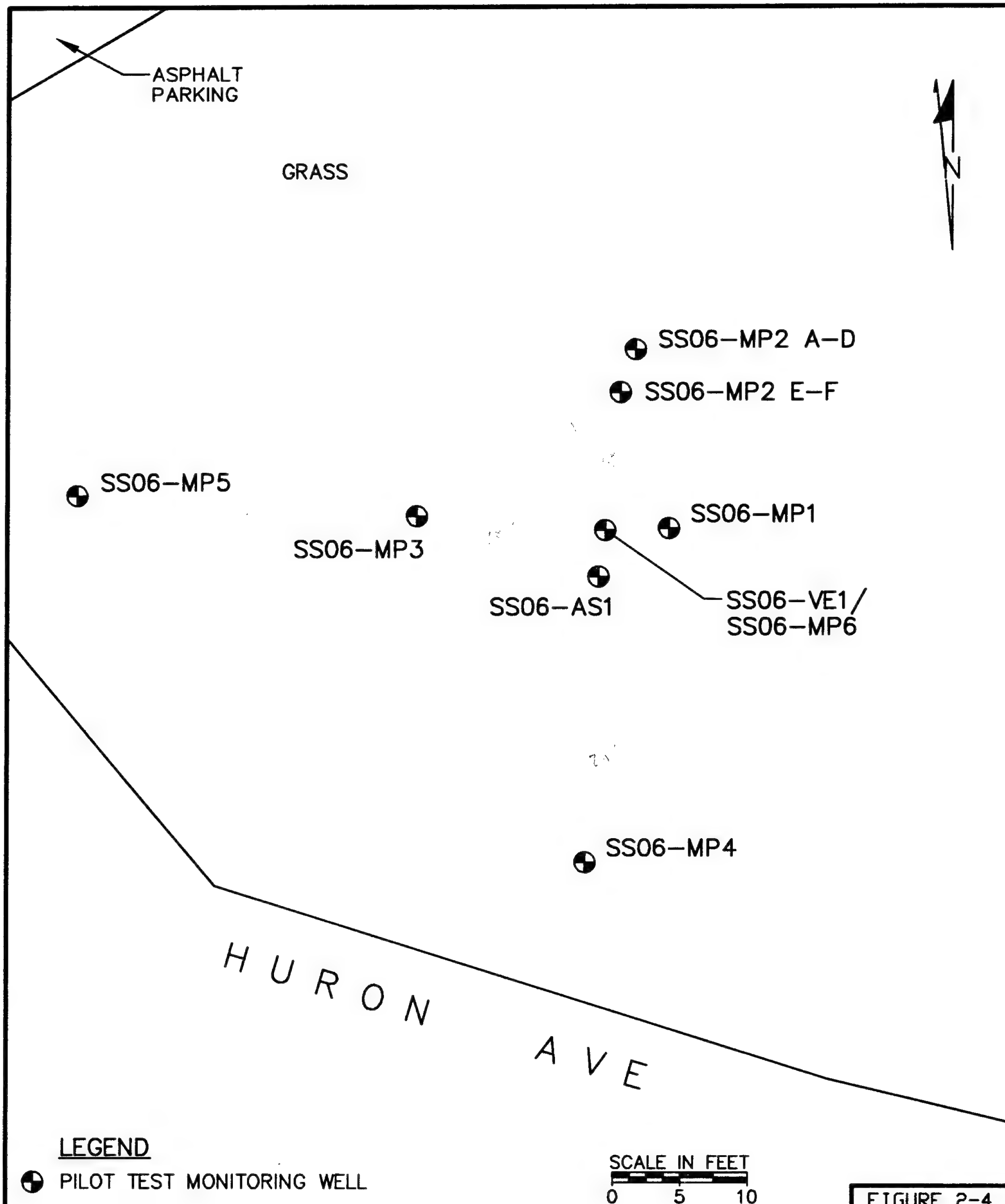


FIGURE 2-4

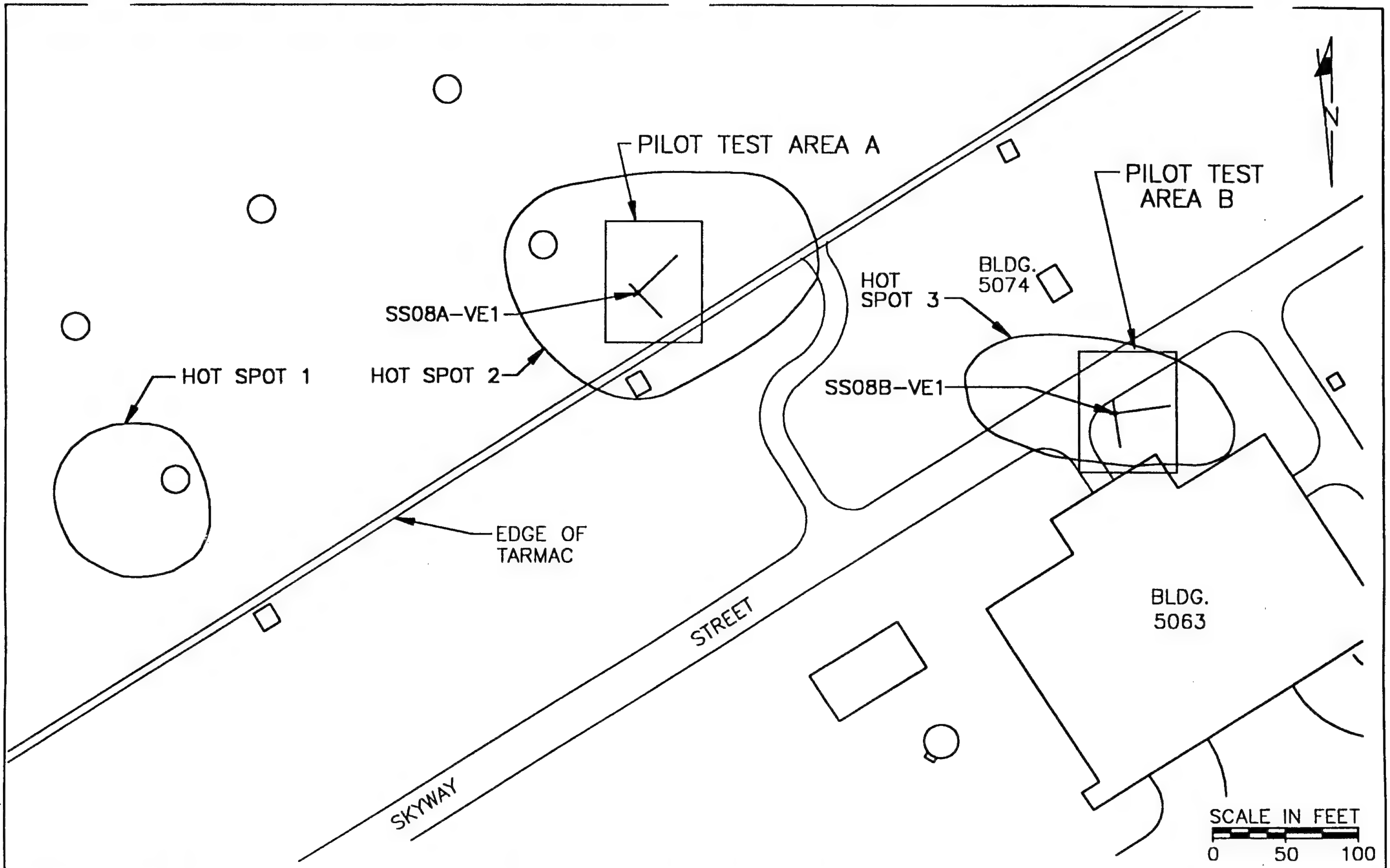
WURTSMITH AIR FORCE BASE

SITE SS-06
PILOT TEST WELL LOCATIONS

AmTech
Engineering, Inc.

DATE: 2/2/98 | DR.: M&E

021746/FRFIG1.DWG



Metcalf & Eddy

WURTSMITH AIR FORCE BASE

SITE SS-08 PILOT TEST LOCATIONS

OSCODA, MICHIGAN

Project Number 021746	
File Name 21746-3	Figure 2-5

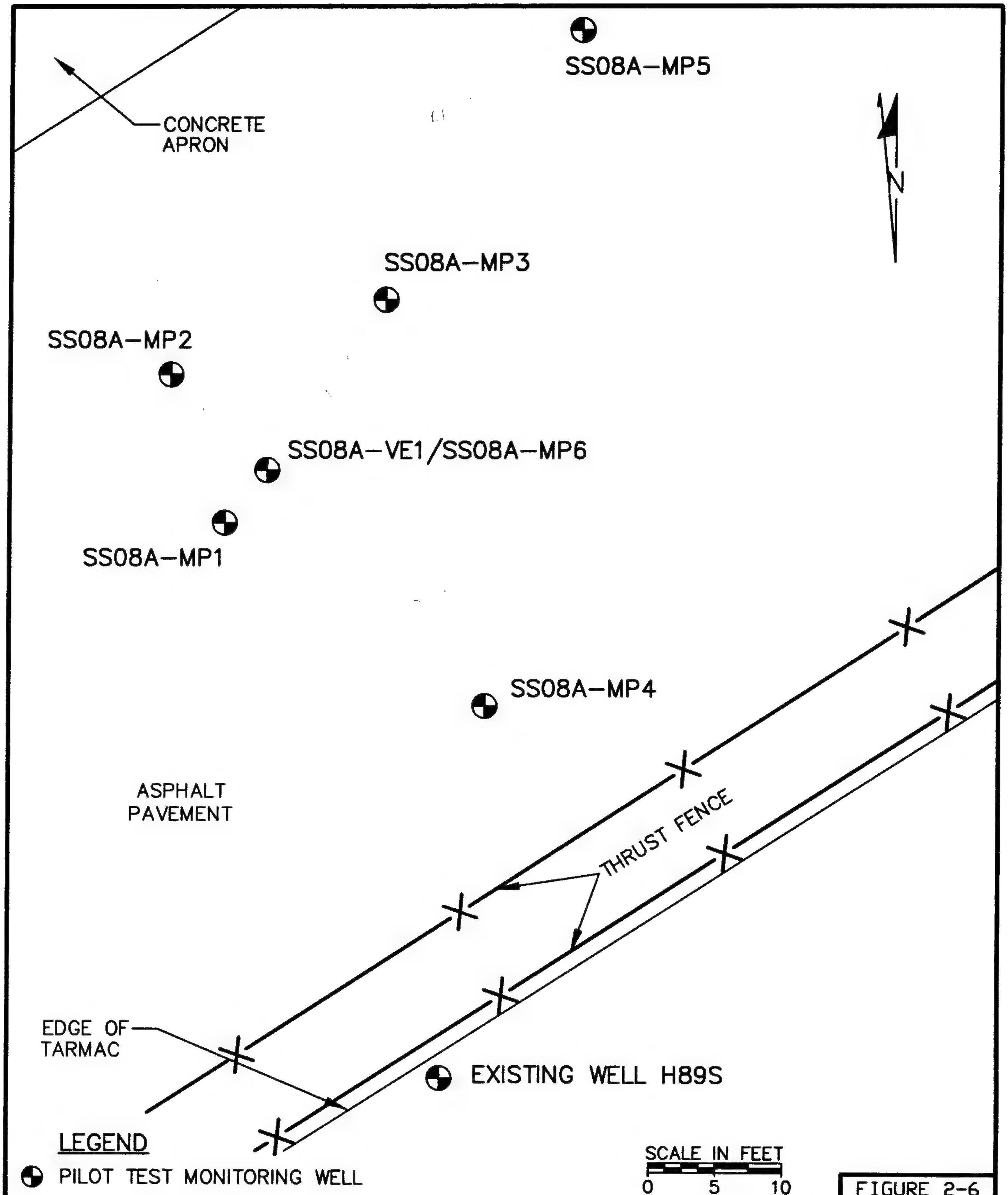


FIGURE 2-6

WURTSMITH AIR FORCE BASE

AmTech Engineering, Inc.

SITE SS-08
PILOT TEST A WELL LOCATIONS

DATE: 2/2/98 | DR.: M&E

021746/FRFIG2.DWG

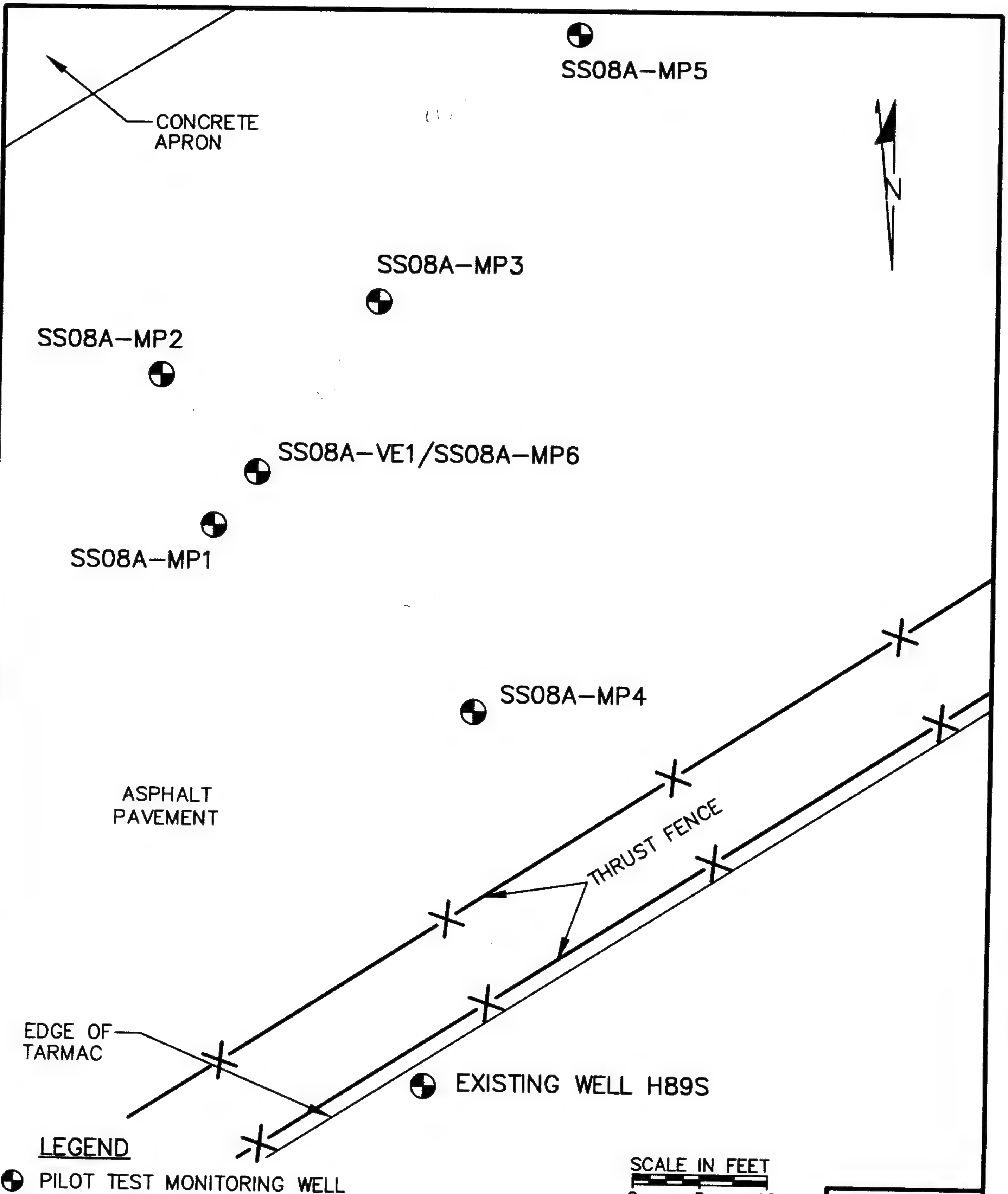


FIGURE 2-6

WURTSMITH AIR FORCE BASE

AmTech
Engineering, Inc.

SITE SS-08
PILOT TEST A WELL LOCATIONS

DATE: 2/2/98

DR.: M&E

021746/FRFIG2.DWG

The layout of the vacuum extraction well (VE-1), air sparge well (AS-1), and monitoring wells for Site SS-08 Location B is shown on Figure 2-7. As with the other sites, the monitoring wells locations were chosen to provide 360 degree coverage around the vacuum extraction and sparge wells and to provide a approximate distances of 5, 10, 15, 25, and 40 feet away from the vacuum extraction and sparge wells.

The locations and elevations of above vapor extraction wells, air sparging wells and monitoring wells were surveyed with respect to other existing monitoring wells and surfacial features, pursuant to Final Quality Program Plan (AmTech, 1997). The well layout shown in Figures 2-4, 2-6 and 2-7 are obtained from the field survey.

Figures 2-8 through 2-10 provide cross-sections through the pilot test areas. Tables 2-1 through 2-3 provide summary information regarding pilot test wells.

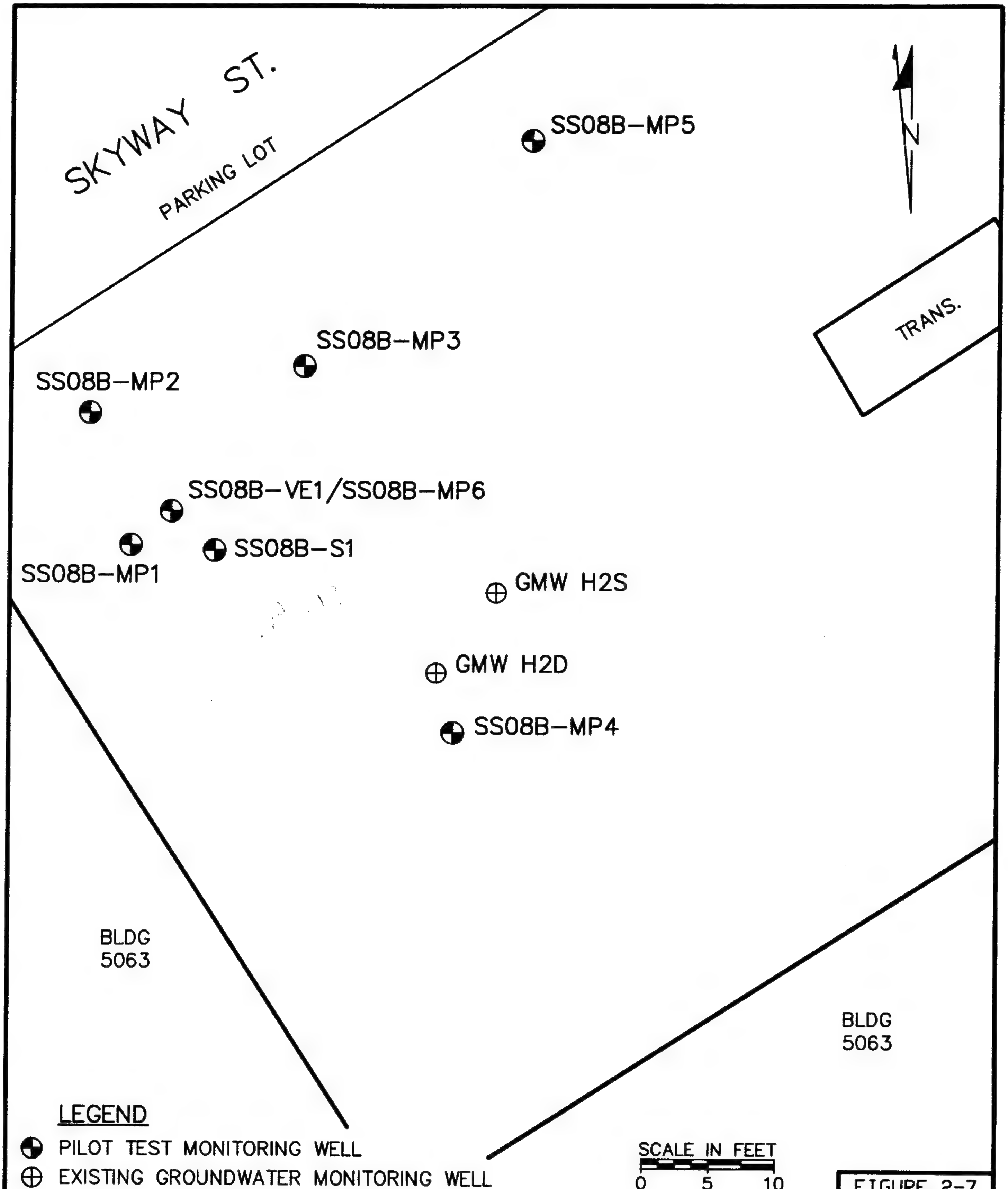


FIGURE 2-7

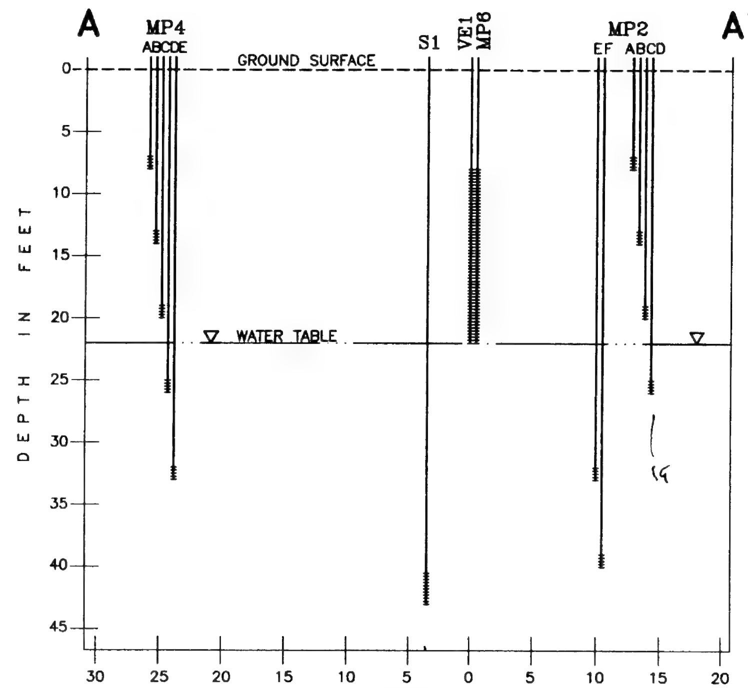
WURTSMITH AIR FORCE BASE

SITE SS-08
PILOT TEST B WELL LOCATIONS

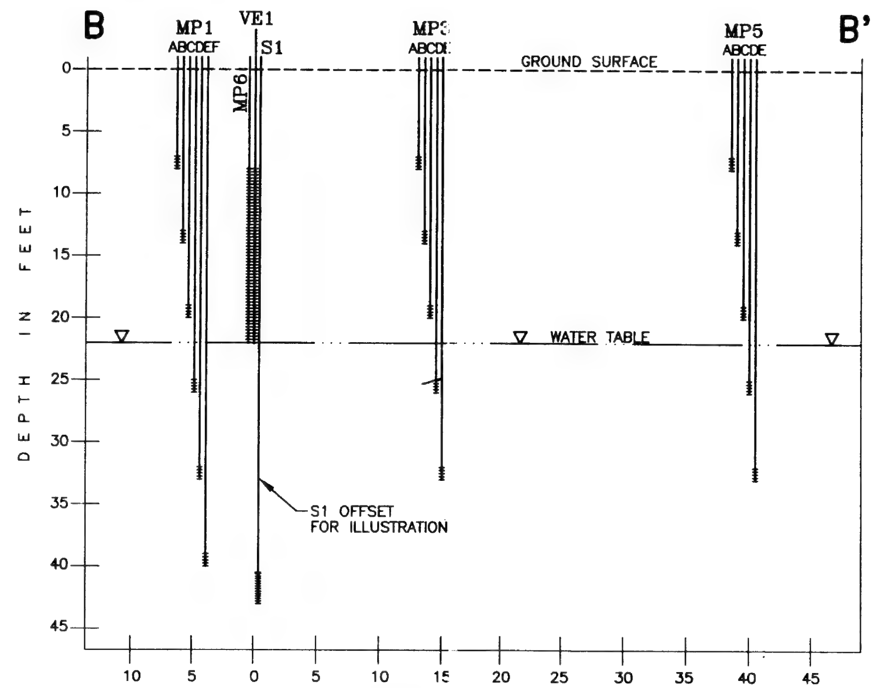
AmTech Engineering, Inc.

DATE: 2/2/98 DR.: M&E

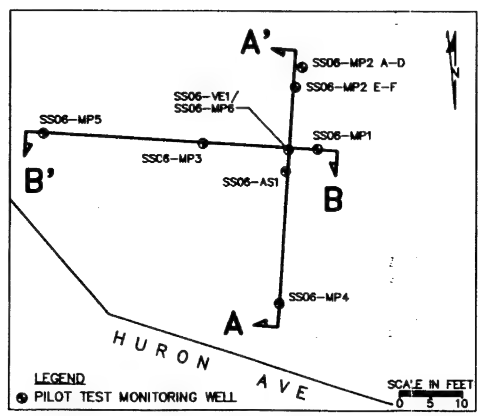
021746/FRFIG3.DWG



CROSS SECTION A–A'



CROSS SECTION B–B'



CROSS SECTION LOCATION MAP

SCALE IN FEET
0 5 10

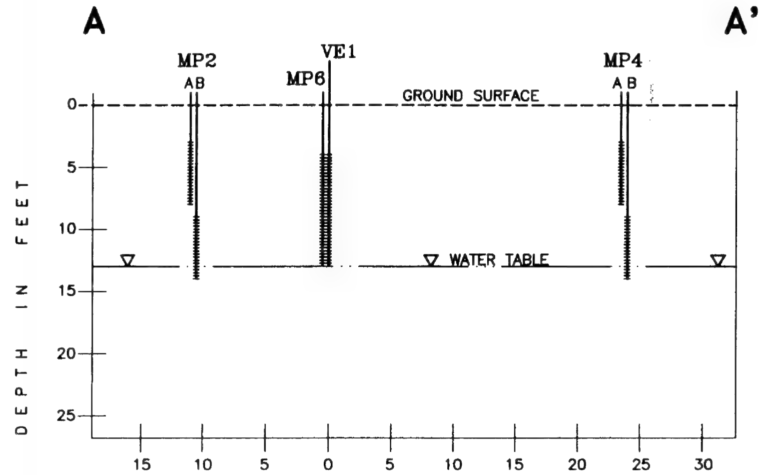
M&E Metcalf & Eddy

WURTSMITH AIR FORCE BASE

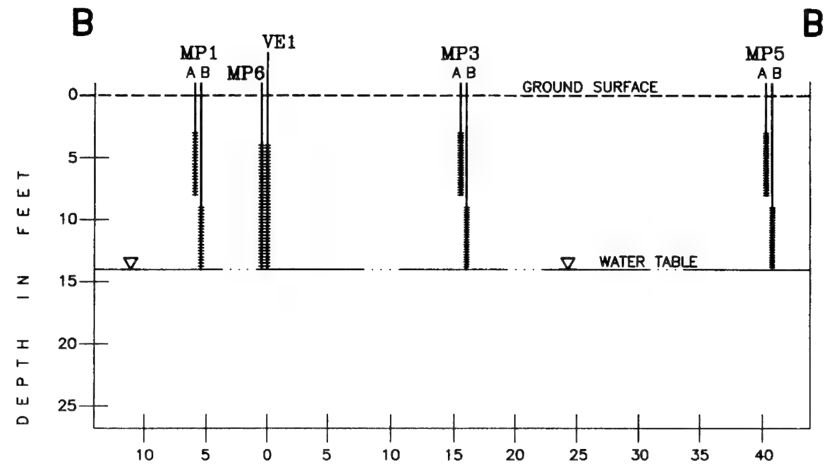
SITE SS–06
CROSS SECTIONS

OSCODA, MICHIGAN

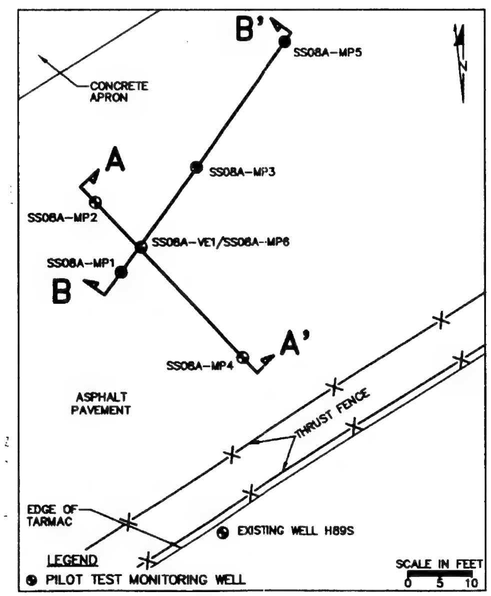
FILE NAME	CHECKED	DRAWN	DATE	PROJECT NO.	FIGURE
21746–9	JP	CAP	FEB 98	021746	2–8



CROSS SECTION A–A'



CROSS SECTION B–B'



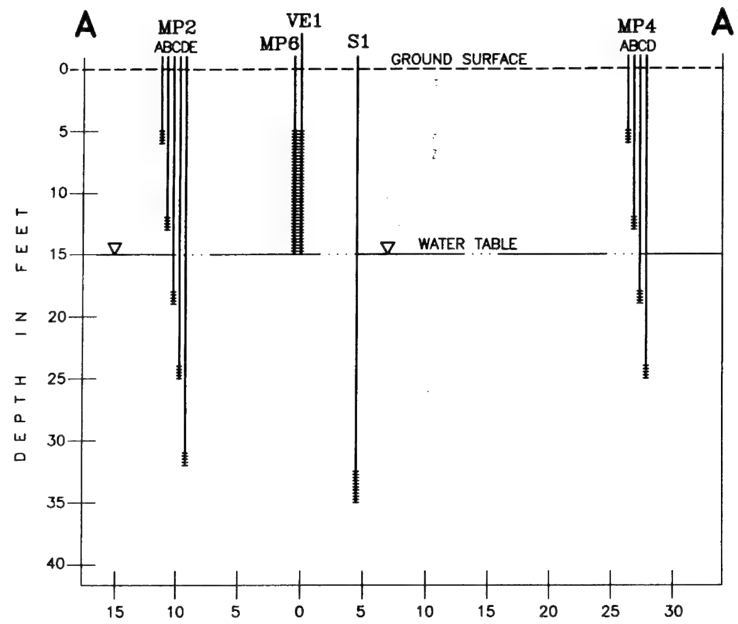
CROSS SECTION LOCATION MAP

SCALE IN FEET
0 2.5 5

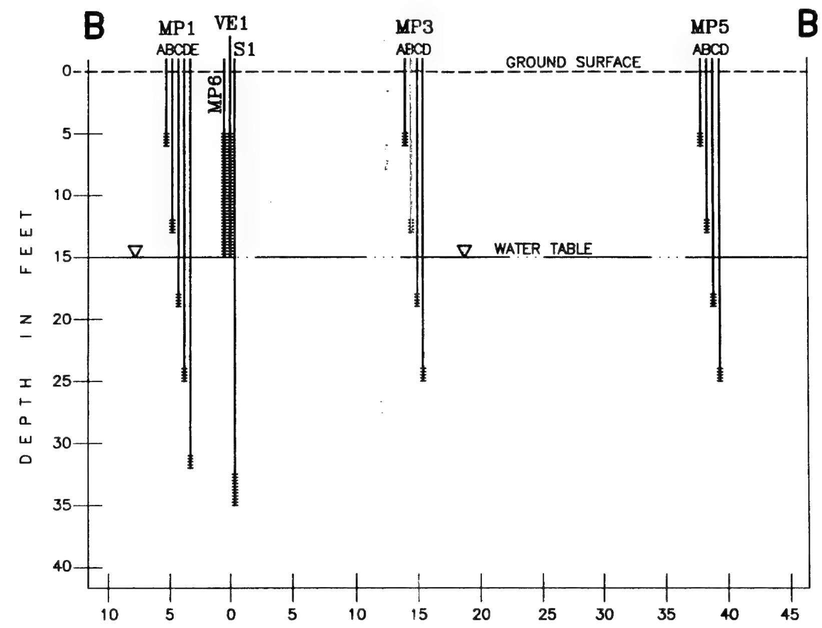
M&E Metcalf & Eddy

WURTSMITH AIR FORCE BASE
SITE SS–08 LOCATION A
CROSS SECTIONS
OSCODA, MICHIGAN

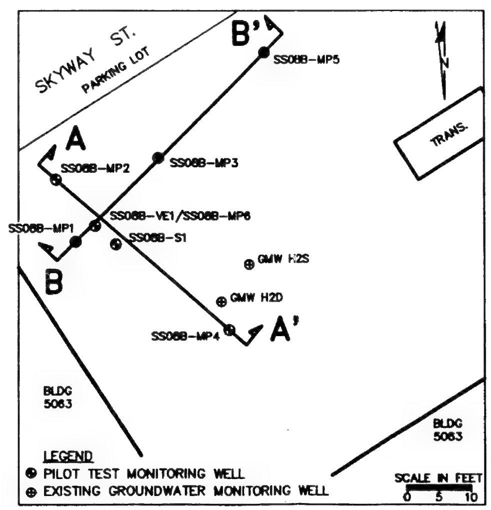
FILE NAME	CHECKED	DRAWN	DATE	PROJECT NO.	FIGURE
21746–9	JP	CAP	FEB 98	021746	2–9



CROSS SECTION A–A'



CROSS SECTION B–B'



CROSS SECTION LOCATION MAP

SCALE IN FEET
0 5 10

M&E Metcalf & Eddy

WURTSMITH AIR FORCE BASE
SITE SS–08 LOCATION B
CROSS SECTIONS
OSCODA, MICHIGAN

FILE NAME	CHECKED	DRAWN	DATE	PROJECT NO.	FIGURE
21746–9	JP	CAP	FEB 98	021746	2–10

TABLE 2-1
MONITORING WELL SCREEN INTERVALS
SITE SS-06
WURTSMITH AFB, MICHIGAN

MONITORING POINT	SCREENED INTERVAL (feet bgs)	WELL DIAMETER (inches)
SS06-VE1	8-23	4
SS06-S1	40.5-43	1
SS06-MP1A	7-8	0.75
SS06-MP1B	13-14	0.75
SS06-MP1C	19-20	0.75
SS06-MP1D	25-26	0.75
SS06-MP1E	32-33	0.75
SS06-MP1F	39-40	0.75
SS06-MP2A	7-8	0.75
SS06-MP2B	13-14	0.75
SS06-MP2C	19-20	0.75
SS06-MP2D	25-26	0.75
SS06-MP2E	32-33	0.75
SS06-MP2F	39-40	0.75
SS06-MP3A	7-8	0.75
SS06-MP3B	13-14	0.75
SS06-MP3C	19-20	0.75
SS06-MP3D	25-26	0.75
SS06-MP3E	32-33	0.75
SS06-MP4A	7-8	0.75
SS06-MP4B	13-14	0.75
SS06-MP4C	19-20	0.75
SS06-MP4D	25-26	0.75
SS06-MP4E	32-33	0.75
SS06-MP5A	7-8	0.75
SS06-MP5B	13-14	0.75
SS06-MP5C	19-20	0.75
SS06-MP5D	25-26	0.75
SS06-MP5E	32-33	0.75
SS06-MP6	8-23	0.75

TABLE 2-2
MONITORING WELL SCREEN LOCATIONS
SITE SS08 LOCATION A
WURTSMITH AFB, MICHIGAN

MONITORING WELL	SCREENED INTERVAL (feet bgs)	WELL DIAMETER (inches)
SS08A-VE1	4-14	4
SS08A-MP1A	3-8	0.75
SS08A-MP1B	9-14	0.75
SS08A-MP2A	3-8	0.75
SS08A-MP2B	9-14	0.75
SS08A-MP3A	3-8	0.75
SS08A-MP3B	9-14	0.75
SS08A-MP4A	3-8	0.75
SS08A-MP4B	9-14	0.75
SS08A-MP5A	3-8	0.75
SS08A-MP5B	9-14	0.75
SS08A-MP6	4-14	0.75

TABLE 2-3
MONITORING WELL SCREEN INTERVALS
SITE SS-08 LOCATION B
WURTSMITH AFB, MICHIGAN

MONITORING WELL	SCREENED INTERVAL (feet bgs)	WELL DIAMETER (inches)
SS08B-VE1	5-15	4
SS08B-S1	32.5-35	1
SS08B-MP1A	5-6	0.75
SS08B-MP1B	12-13	0.75
SS08B-MP1C	17-19	0.75
SS08B-MP1D	24-25	0.75
SS08B-MP1E	31-32	0.75
SS08B-MP2A	5-6	0.75
SS08B-MP2B	12-13	0.75
SS08B-MP2C	18-19	0.75
SS08B-MP2D	24-25	0.75
SS08B-MP2E	31-32	0.75
SS08B-MP3A	5-6	0.75
SS08B-MP3B	12-13	0.75
SS08B-MP3C	18-19	0.75
SS08B-MP3D	24-25	0.75
SS08B-MP4A	5-6	0.75
SS08B-MP4B	12-13	0.75
SS08B-MP4C	18-19	0.75
SS08B-MP4D	24-25	0.75
SS08B-MP5A	5-6	0.75
SS08B-MP5B	12-13	0.75
SS08B-MP5C	18-19	0.75
SS08B-MP5D	24-25	0.75
SS08B-MP6	5-15	0.75

3.0 TEST METHODS

3.1 SOIL BORINGS AND WELL INSTALLATION

Soil Borings, well installation and development of wells were performed by American Environmental Corporation. These tasks were started on October 28, 1997, and completed on November 15, 1997.

At each of the three sites, one soil boring was sampled for lithology. Lithology sampling was completed by continuously sampling with split spoon sampler and completing a detailed boring log as described in the Final Quality Program Plan (AmTech, 1997). At sites SS-06 and SS-08 Location A, the air sparging (AS) well was sampled for lithology. This was the first boring completed at these sites and was the deepest boring. An AS well was not installed at Site SS-08 Location A, pursuant to the Final Quality Program Plan (AmTech, 1997), but the first boring installed at this site was sampled as described above.

Following the first boring, with detailed lithology sampling, each of the remaining borings were logged at five foot intervals from soil cuttings until the total depth of each boring was reached.

The wells at each site were installed according to the specifications noted in the Field Sampling Plan (AmTech, 1997). Boring logs and well construction diagrams are included in Appendix A.

3.2 STEPPED VACUUM TESTS

3.2.1 Test Description

A stepped vacuum test is conducted to establish a relationship curve between applied vacuum and flow rate for the formation/extraction well. The purpose for this curve is to aid in determining the flow rate that can be expected from a given applied vacuum and to aid in establishing an optimal flow rate for a single well in the formation.

3.2.2 Test Methods

To conduct stepped rate vacuum tests, the pilot vacuum extraction system described in Section 2.1 was connected to the vapor extraction wellhead. The vacuum blower(s) were then turned on with the air inlet valve (see Figure 2-1) fully open. This resulted in a minimal vacuum applied to the formation. The flow rate obtained with this minimal vacuum was recorded until it stabilized. After a stable reading was recorded, the air inlet valve was closed somewhat to increase the vacuum in the SVE well, and the flow rate was again allowed to stabilize and was recorded. This process was repeated in regular vacuum steps until the maximum flow rate/vacuum combination for the test equipment and formation was reached. Following this, the test was repeated with decreasing steps in vacuum.

To analyze the test, the flow rate was plotted against applied vacuum for the test data. The result is a system curve for the well. The curve can be used to evaluate the expected flow rate from a similar extraction well in the formation under a known applied vacuum. If the curve exhibits a maximum point, the maximum expected flow rate can be determined and the vacuum that will generate this flow rate can be established. If the curve does not exhibit a maximum point, then the maximum flow rate and corresponding vacuum must be estimated using calculated air permeability and an air flow model.

3.3 CONSTANT RATE STEADY-STATE TESTS

A constant rate steady state vapor extraction test is used to estimate the air permeability of the formation. At a given flow rate and vacuum at the extraction well, a steady state vacuum in

vadose zone observation wells will be established if vapor extraction is continued for a sufficiently long period of time. Several analytical equations are used for estimating the air permeability of the formation based on the steady state vacuum present in vadose zone observation wells. The test can be performed at any flow rate and vacuum that provides sufficient vacuum readings at the observation well(s) for the sensitivity of the instruments used to detect the vacuum.

The time required to reach steady state varies considerably based on the permeability and specific storage of the formation. The time can be as little as a few minutes or as long as several days. An estimate of the time required to reach steady state is calculated using Equation 1.

$$t = \frac{r^2 n_a \mu}{4 k_a P_{atm}} \qquad \text{Equation 1}$$

Where:
- t = time required to reach steady state (T)
- r = distance from vapor extraction well to observation well (L)
- n_a = air filled porosity of the formation (L^3/L^3)
- μ = dynamic viscosity of the soil gas (M/LT)
- k_a = effective air permeability of the formation (L^2)
- P_{atm} = absolute atmospheric pressure (M/LT^2)

Of course, this equation assumes that the air filled porosity and effective air permeability of the formation are already known. The equation is useful for estimating how long a steady state test must be run if estimates of these parameters can be made prior to the test. In actual practice, the test is run until vacuum measured at observation wells is no longer increasing and Equation 1 is used to verify that the test has been run long enough after preliminary calculations of air permeability and air filled porosity have been completed. The pseudo steady

state method does not assume the attainment of steady state and can be applied as described below.

3.3.1 Test Methods

To conduct the steady state test, the pilot vacuum extraction system described in Section 2.1 was connected to the vacuum extraction well as described in Section 2.3. The air inlet valve on the extraction system was set to provide the desired vacuum and flow rate for the test. The vacuum system was turned on and vacuum readings at observation wells were taken periodically. The test was continued at a constant extraction rate until the vacuums at all of the observation wells had reached steady state. Barometric pressure readings were recorded continuously during the tests and in the periods before and after the tests.

3.3.2 Test Analysis

The steady state data were analyzed using three methods to obtain estimates of air permeability. The first method requires a steady state vacuum at a single observation well and an estimated radius of vacuum influence in the formation. This method is referred to here as the effective radius method. The second method requires steady state vacuum readings from two observation wells located at different distances from the extraction well. The second method is referred to here as the two well steady state method. The first and second methods assume that steady state has been reached prior to data collection (Equation 1). The third method does not assume steady state but only assumes that the data are collected at the same time at two observation wells located at two distances from the extraction well. The third method is referred to here as the pseudo steady state method.

The three methods each assume fully penetrating extraction wells and fully penetrating observation wells. At all three sites, the extraction well penetrated enough of the vadose zone to make the assumption of full penetration reasonable. However, the observation wells were

partially penetrating by design in all cases. To obtain an approximation of full penetration, the vacuum readings at the two or three screened intervals at each observation well location were averaged. The partially penetrating wells were spaced evenly across the vadose zone. Therefore, the average vacuum from the nest of partially penetrating wells provided a good approximation of the vacuum that would be observed with a fully penetrating observation well.

Radius of Influence Method

For horizontal radial flow to a vacuum extraction well (line sink), Equation 2 can be used to calculate the effective air permeability of the formation at steady state.

$$k_a = \frac{Q_v P^* \mu}{\pi b \left(P^2 - P_{atm}^2\right)} \ln\left(\frac{r_e}{r}\right) \qquad \text{Equation 2}$$

Where:
k_a = effective air permeability of the formation (L^2)
Q_v = volumetric flow rate from the extraction well (L^3/T)
P^* = absolute pressure in the formation at the extraction well (M/LT^2)
u = dynamic viscosity of the soil gas (M/LT)
r_e = the effective radius of vacuum influence (L)
r = distance from the extraction well to the observation well (L)
b = the thickness of the vadose zone (L)
P = absolute pressure in the observation well (M/LT^2)
P_{atm} = the atmospheric pressure (M/LT^2)

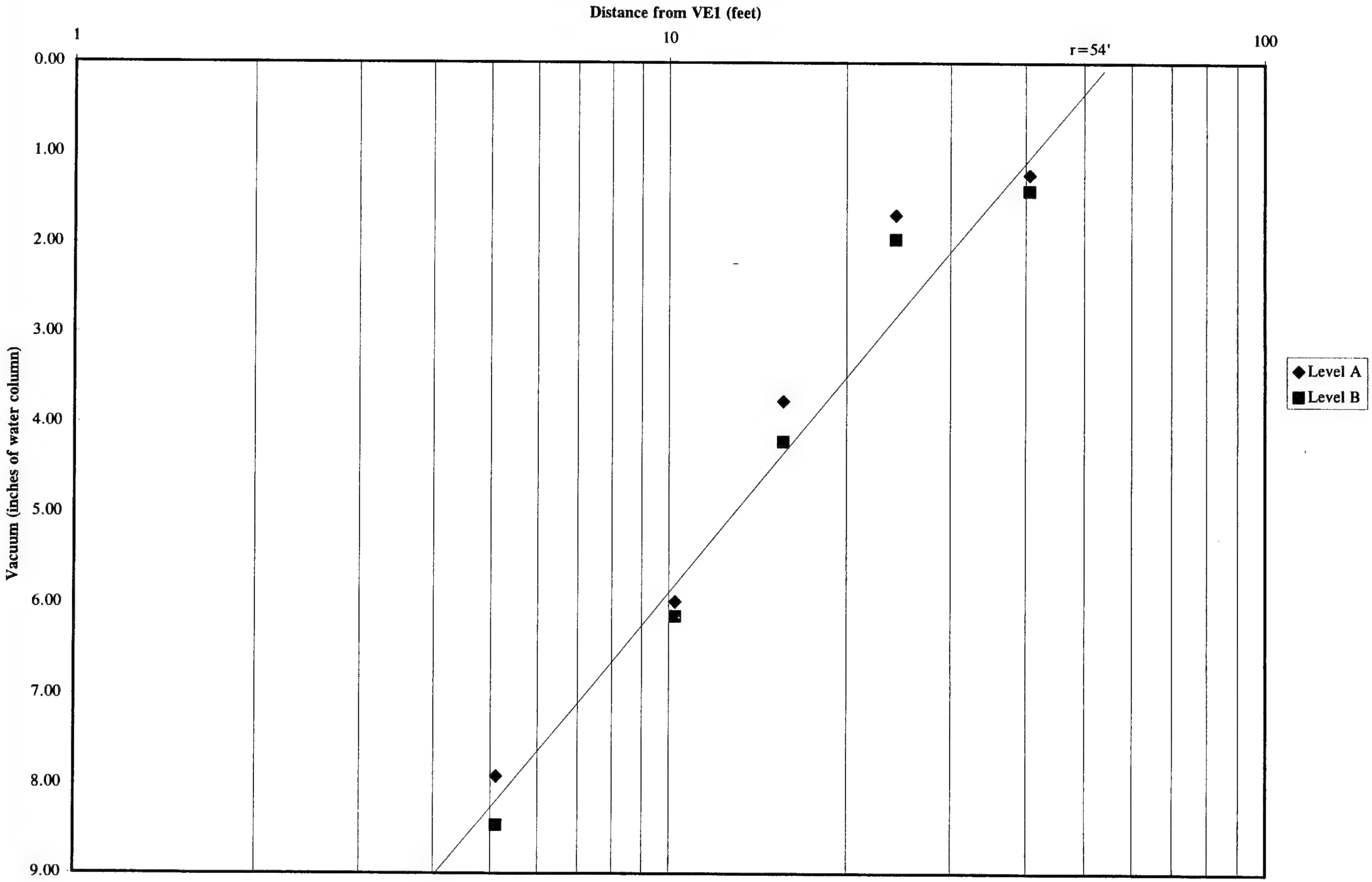
To determine the formation air permeability using Equation 2, it is first necessary to estimate the radius of vacuum influence for the formation. Estimating this parameter is somewhat problematic. Mass balance dictates that for a formation with an impermeable upper and lower boundary the radius of influence is time dependent and increases with time. The analysis of

transient radial flow indicates that the radius of influence increases in proportion to the square root of time (McWhorter and Sunada, 1977) .

In actual practice, the upper boundary is rarely impermeable and the radius of influence often reaches a steady state and shows little change with time (Beckett and Huntly, 1994). Assuming that the radius of vacuum influence reaches a steady state in the test, this parameter can be estimated using methods analogous to distance drawdown plots used in groundwater pumping test analysis (US Army Corps of Engineers, 1995). The method involves plotting the vacuum response at observation wells (at steady state) against the log of the radial distance between the observation wells and the extraction well. Figure 3-1 provides an example distance drawdown plot for Site SS-08 location A. The radius of influence is estimated by providing a best fit line to the data (least squares method) and extending the line to the point where it crosses the zero vacuum line. The radius at which the lines crosses zero vacuum is considered an estimate of the radius of vacuum influence. For the data presented in Figure 3-1 the radius is approximately 54 feet.

It should also be noted that P^* in Equation 2 represents the formation vacuum at the location of the vacuum extraction well and not the vacuum observed at the extraction wellhead. The vacuum at the extraction wellhead includes well losses for the entry of air into the well and within the well casing. Considerable error in the calculation of air permeability can result from using the extraction wellhead vacuum, particularly at higher applied vacuums. The best practice is to utilize a piezometer installed outside the extraction well but within the same borehole as the extraction well to provide measurements of formation vacuum. This is the method that was employed for this test.

FIGURE 3-1
STEADY STATE DISTANCE DRAWDOWN PLOT
SS-08 LOCATION A
WURTSMITH AFB, MICHIGAN



Two Well Steady State Method

For horizontal radial flow to an extraction well (line sink), Equation 3 can be used to calculate air permeability in the formation at steady state.

$$k_a = \frac{Q_v P^{*} \mu}{\pi b \left(P_1^2 - P_2^2\right)} \ln\left(\frac{r_2}{r_1}\right) \qquad \text{Equation 3}$$

Where:
- k_a = effective air permeability of the formation (L^2)
- Q_v = volumetric flow rate from the extraction well (L^3/T)
- P^* = absolute pressure in the formation at the extraction well (M/LT^2)
- u = dynamic viscosity of the soil gas (M/LT)
- b = the thickness of the vadose zone (L)
- P_1 = absolute pressure at the closer observation well (M/LT^2)
- P_2 = absolute pressure at the more distant observation well (M/LT^2)
- r_1 = distance from the extraction well to the closer observation well (L)
- r_2 = distance from the extraction well to the more distant observation well (L)

As discussed for Equation 2, P^* in Equation 3 represents the formation vacuum at the location of the vacuum extraction well and not the vacuum observed at the extraction wellhead. The best practice is to utilize a piezometer installed outside the extraction well but within the same borehole as the extraction well to provide measurements of formation vacuum.

Pseudo Steady State Method

This analytical method assumes radial, one-dimensional flow to the extraction well, but does not actually depend on the attainment of steady state. This solution depends on the use of an approximation commonly known as the Cooper-Jacob approximation to the Theis solution of the partial differential equation for transient fluid flow. These methods are best known for

analysis of groundwater pumping test data, but by treating air as an incompressible fluid, the air flow equations can be written in the same form as groundwater flow equations. The mathematical basis for these methods were proposed by Johnson, Kemblowski, and Colthart (1990).

For appropriate application of the Cooper-Jacob approximation, the Boltzmann variable u should be less than or equal to 0.01 as calculated for air flow in Equation 4.

$$u = \frac{r^2 n_a \mu}{4 k_a P_{atm} t} \qquad \text{Equation 4}$$

Where: u = Boltzmann variable

r = distance from vapor extraction well to observation well (L)

n_a = air filled porosity of the formation (L^3/L^3)

μ = dynamic viscosity of the soil gas (M/LT)

k_a = effective air permeability of the formation (L^2)

P_{atm} = absolute atmospheric pressure (M/LT^2)

t = the time at which the measurement is taken (T)

Calculation of the Boltzmann variable depends on a prior knowledge of the formation air permeability and air filled porosity. These values can be assumed prior to the test to judge when application of this method is appropriate. In actual practice, the data are collected and analyzed assuming that the Boltzmann variable is sufficiently small. Then a calculated value of air permeability and an assumed value of air filled porosity are entered into Equation 4 to verify that the solution was appropriate. Calculated values for air filled porosity are also possible using transient analyses.

The Cooper-Jacob method can be applied prior to reaching steady state provided that the measurements at the two observation wells are taken at approximately the same time and

provided that u is less than or equal to 0.01. Air permeability is calculated with this method using Equation 5.

$$k_a = \frac{Q_v \mu}{4\pi b(P_2 - P_1)}\left(\ln\frac{r_2}{r_1}\right) \qquad \text{Equation 5}$$

Where: k_a = effective air permeability of the formation (L^2)

Q_v = volumetric flow rate from the extraction well (L^3/T)

P_1 = absolute pressure in the formation at the closer observation well (M/LT^2)

P_2 = absolute pressure in the formation at the further observation well (M/LT^2)

μ = dynamic viscosity of the soil gas (M/LT)

r_1 = distance from the extraction well to the closer observation well (L)

r_2 = distance from the extraction well to the more distant observation well (L)

b = the thickness of the vadose zone (L)

The reason that this method works prior to attainment of steady state is that while the vacuum at the observation wells may be changing with time, the difference in pressure between any two observation points remains consistent over time (McWhorter and Sunada, 1977).

3.4 CONSTANT FLOW TRANSIENT TESTS

Transient solutions for constant rate tests are used to determine the formation air permeability prior to redistribution of soil moisture as a result of induced vacuum or pressure. This method for determining soil permeability has some advantages over steady state methods. Transient methods allow the inclusion of air leakage from the surface into the analysis and they can be used, in some cases to evaluate the vertical permeability of the formation (in addition to the horizontal permeability). The relative permeability of the surface cover can also be evaluated.

3.4.1 Constant Flow Transient Test Methods

The collection of data for analysis with transient methods generally requires rapid data collection to obtain sufficient early time data for analysis. For most formations suitable for soil vapor extraction technology, this requires the use of a data recording device. For these pilot tests, a four channel Hermit™ data logger and three pressure transducers were used. For the tests conducted at SS-08 Location A, a junction box was also required for each transducer to allow a pressure transducer to collect vacuum data. The junction box allowed the transducer (which will normally only measure pressure) to measure vacuum by applying the vacuum to the back side of the transducer strain gauge. At the other two sites, the transient tests were conducted using pressure injection (rather than vacuum withdrawal) so the transducers could be used directly for measurement without junction boxes.

The pilot test vapor extraction equipment used for the test is described in Section 2.1. Transducers were connected to selected monitoring wellheads using flexible tubing and barbed or compression fittings. The connection between the transducer and the flexible tube was completed using the threaded pipe fitting present on the transducer and a threaded pipe to compression tube fitting.

Three wells were tested simultaneously using the three transducers. The data logger was set to collect data with very short initial time intervals increasing logarithmically to a maximum interval of five minutes. The appropriate transducer parameters were entered into the data logger to provide measurements in pounds per square inch (psi).

The vapor extraction equipment was set to the desired flow prior to the start of the test. To start each test, the blower was turned on at the same time that the data logger was started. After the test had run for a sufficient period of time, the blower was turned off and the data logger was "stepped" at the same time, allowing rapid data collection during the recovery of

the well to static conditions. This procedure was repeated for each set of observation wells. Barometric pressure during the tests was also recorded for use in analysis. The time interval of the tests was short enough so that barometric corrections were unnecessary.

The vacuum extraction flow rate was recorded during the tests using a pitot tube as described in Section 2.1. The temperature of the extracted vapor was also measured for use in the equations to convert pitot tube measurements to standard cubic feet per minute (scfm) measurements.

3.4.2 Analysis Methods

Johnson *et al* (1990) proposed linearizing the partial differential equation for transient flow by expressing the P^2 term in the equation as the product of atmospheric pressure and a deviation from atmospheric pressure. The resulting equation was of the same form as the Boussinesq equation used in groundwater flow analysis, allowing an analogous solution methodology. Massmann (1989) determined that the error introduced by this assumption was negligible for vacuums less than 0.2 atmospheres.

The solution to the linearized equation for one dimensional radial flow to a vapor extraction well, assuming a constant sink at the extraction well and $P = P_{atm}$ at $r = \infty$ is provided as Equation 6.

$$P - P_{atm} = \frac{Q_v \mu}{4\pi b k_a} \int_u^\infty \frac{e^{-x}}{x} dx \qquad \text{Equation 6}$$

Where: $u = \dfrac{r^2 n_a \mu}{4 k_a P_{atm} t}$

and u = Boltzmann variable

r = distance from vapor extraction well to observation well (L)

n_a = air filled porosity of the formation (L^3/L^3)

μ = dynamic viscosity of the soil gas (M/LT)

k_a = effective air permeability of the formation (L^2)

P_{atm} = absolute atmospheric pressure (M/LT^2)

t = the time at which the measurement is taken (T)

k_a = effective air permeability of the formation (L^2)

Q_v = volumetric flow rate from the extraction well (L^3/T)

P = absolute pressure in the formation at an observation well (M/LT^2)

r = distance from the extraction well to the observation well (L)

b = the thickness of the vadose zone (L)

x = a dummy variable of integration

The integral in Equation 6 is known as the Theis well function (Theis, 1935). This well function is commonly used in analysis of transient pumping test data in aquifers. Related functions have also been developed for leaky radial flow (Hantush and Jacob, 1955), and radial leaky flow with partial penetration (Hantush, 1965).

For the tests at this site, the well function for leaky radial flow (Hantush 1955) was used, resulting in Equation 7.

$$k_a = \frac{Q_v \mu}{4\pi b\left(P - P_{atm}\right)} W\left(u, \frac{r}{B}\right) \qquad \text{Equation 7}$$

where: $W(u,r/B)$ = the leaky well function (Hantush, 1965)

other variables are as defined above for Equation 6

To solve for soil air permeability, the transient data are plotted with vacuum versus time on a log-log scale. The plots are compared to "type curves" for the leaky well function by the methods used in groundwater analysis (Theis, 1935; Hantush and Jacob, 1955; Hantush, 1961). A match point between the curves is chosen and the values of vacuum and time are recorded from the data plot and W(u,r/B) and 1/u are recorded from the type curve. These values are then entered into Equation 7 to obtain the formation air permeability.

Figure 3-2 is a plot of the type curves generated for analysis of the transient data. Figure 3-3 is a plot of data from the transient test conducted at SS-06 well MP1C plotted on the same log-log scale as the type curve. The type curve plot was photocopied onto transparent paper to allow easy matching between the air permeability test data and the type curve.

Equation 8 provides a method for calculating the air filled porosity of the formation using the data obtained from the type curve match.

$$n_a = \frac{4k_a P_{atm} t}{r^2 \mu} u \qquad \text{Equation 8}$$

where: variables are as defined above (Equation 6)

The transient analytical methods described here allow potentially more accurate estimations of soil air permeability by including surface leakage. Beckett and Huntly (1994) found a superior fit to data using leaky well functions and concluded that air leakage from the surface is the rule rather than the exception for vapor extraction systems.

The transient analysis methods described above assume full penetration of the extraction well and observation wells. The extraction well is close enough to fully penetrating at each site to neglect the effects of partial penetration. However, the observation wells clearly are partially

FIGURE 3-2
TYPE CURVES FOR LEAKY, CONFINED, TRANSIENT MODEL
WURTSMITH AFB, MICHIGAN

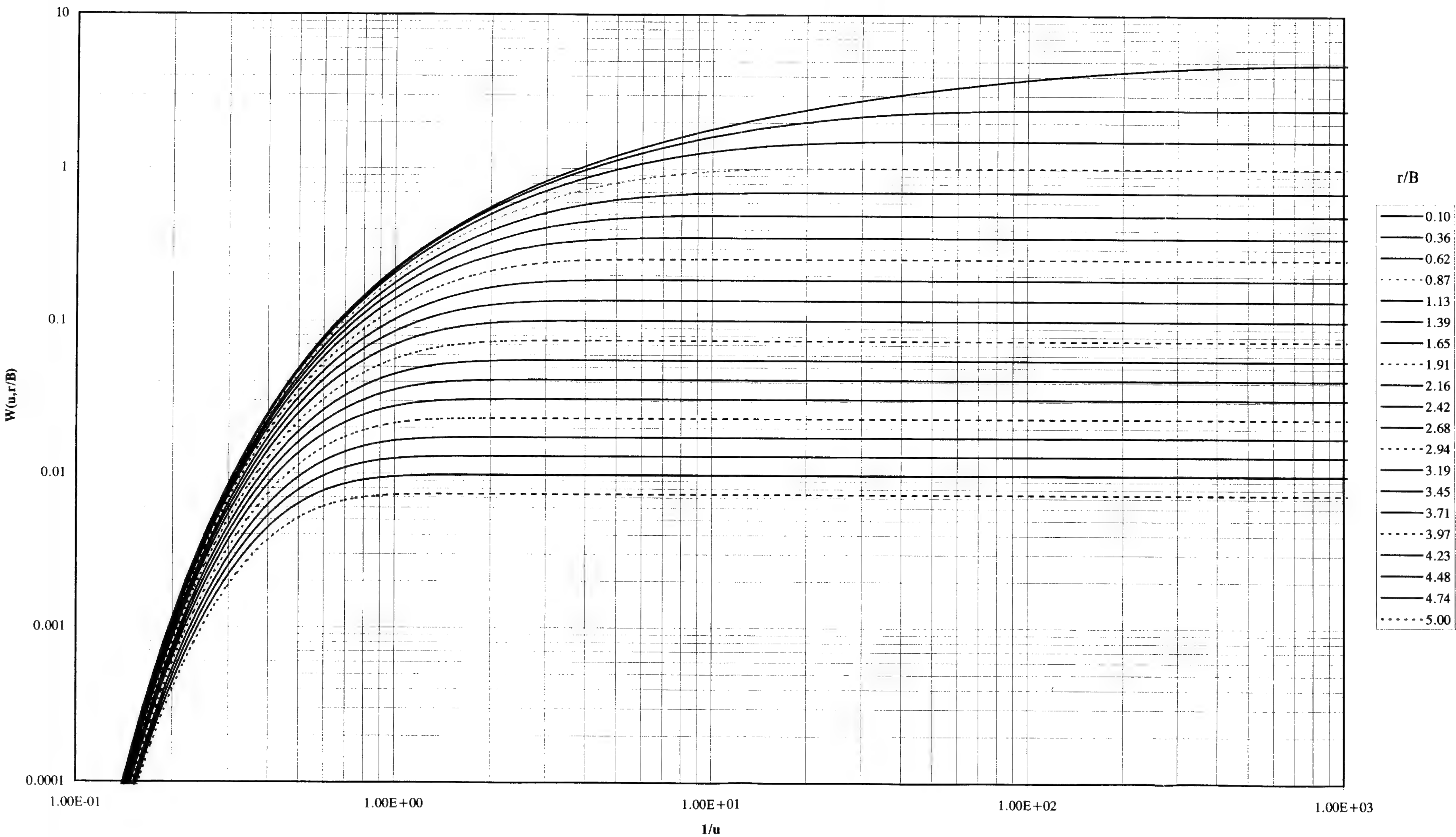
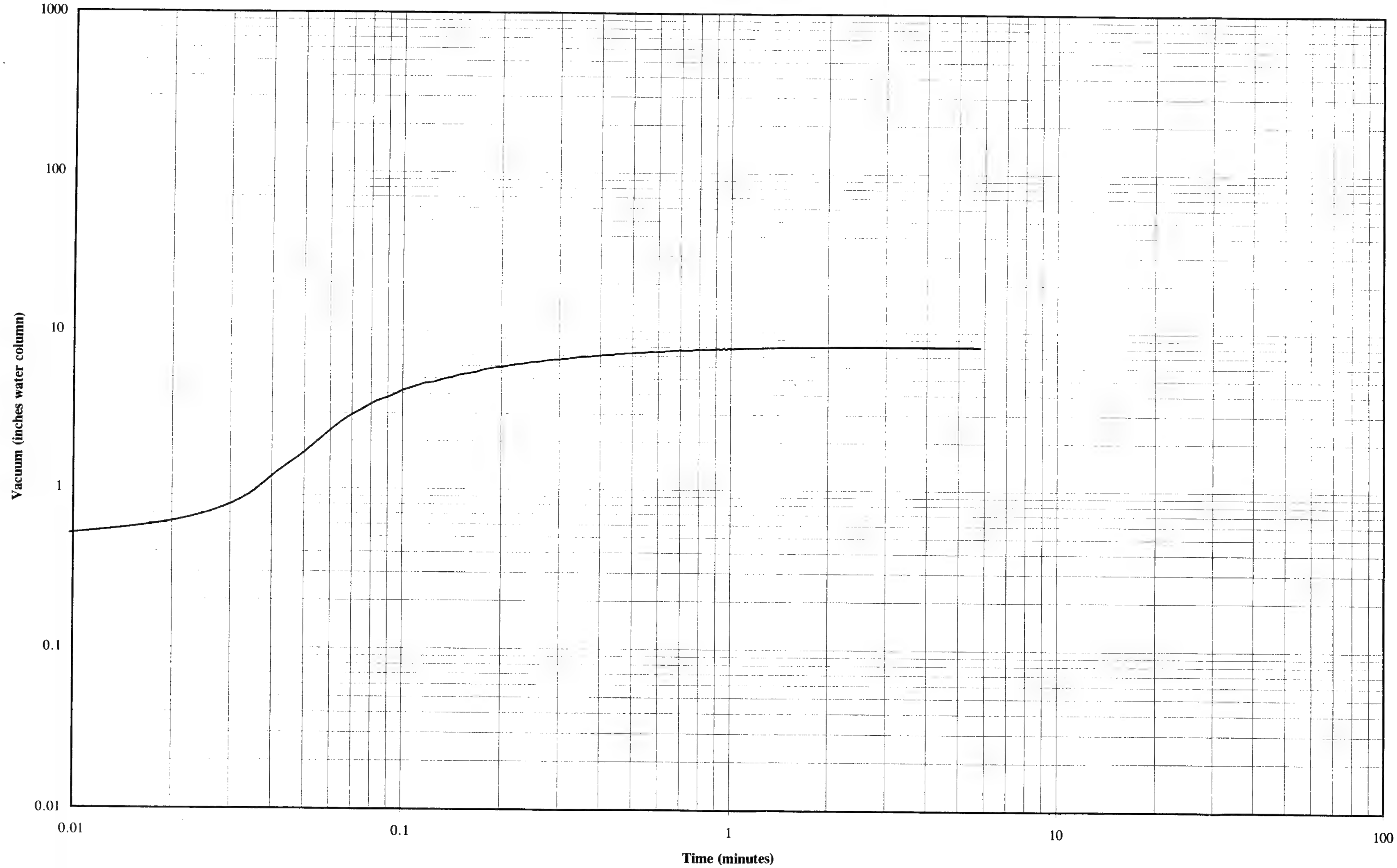


FIGURE 3-3
WELL MP1C TRANSIENT DATA
SITE SS-06
WURTSMITH AFB, MICHIGAN



penetrating. It is possible to analyze the data with type curves which account for partial penetration, but these methods require assumptions that reduce the viability of the comparisons. It was also not possible to average the data as was done for the steady state tests as the curve shapes and magnitudes were different at different depths. Instead, the air permeability and air filled porosity were calculated for each depth and the calculated values were averaged. The only realistic way to utilize all of the information available from the well set-up was by using a numerical flow model. This method is described below in Section 3.8.

3.5 EXTENDED VAPOR EXTRACTION TEST

Following completion of the air permeability testing, the operation of the pilot test SVE system was continued to provide a better measure of the expected concentration of volatile organic constituents under long term extraction and to provide a stable baseline volatile load prior to the initiation of air sparging.

This extended vapor extraction pilot was conducted only at Site SS-06. At Site SS-08 Location A the volatile load observed during the air permeability testing was very low and air sparging was not planned for this site. At SS-08 Location B the observed volatile load was also very low and was stable within a short period of time allowing the sparge test to be started without an extended period of vapor extraction.

Soil gas was sampled for field parameters for a period beginning before the start of vapor extraction until after the end of the air sparging tests. Soil gas samples were obtained from each of the monitoring wells an average of once per day throughout this period. Soil gas samples were also obtained from the extracted gas prior to entering the blower system (port 1 in Figure 2-1), after the vapor extraction and before the carbon treatment system (port 4 in Figure 2-1), between the first and second of the carbon vessels (port 5 in Figure 2-1), and after the second series carbon vessels.

The field parameters analyzed included percent oxygen, percent carbon dioxide, percent methane, total volatiles, and percent helium. The instruments used to analyze the soil gas are described in Section 2.3. Helium measurements were made in the initial background measurements to verify that no helium was present naturally in the formation and then helium measurements were not made again until helium injection began as a part of the air sparging test.

Soil gas samples for field parameters were obtained from the vadose zone wells and from the sampling ports using a purging pump connected to the wellhead using polyethylene tubing. The tubing was connected to the wellhead with a barbed connector attached to a ball valve at the wellhead. The primary purging action was supplied by an air sampling pump. The gas analysis instruments were connected to the purge air line with "y" connections such that they pulled samples from the purging air stream.

Purging with the sample pump and the gas analysis instruments was continuous prior to, during and after obtaining each sample. The gas analysis instruments were monitored until the atmospheric air was purged from the tube and initial parameter concentrations were recorded. The purging and gas analysis then continued for a period of approximately 15 minutes at each location. Parameter values were recorded at intervals ranging from two minutes to five minutes. Readings were continued until stable values were obtained for each parameter. The final readings were then taken as the data point for each sampling event (although the intermediate recordings were maintained for documentation of appropriate purging and of the stability of the readings).

Soil gas samples were also obtained on four occasions for laboratory analysis of volatile organic compounds. These samples were collected near the near the end of the period of vapor extraction only at sites SS-06 and SS-08 Location B (prior to the start of air sparging), and near the end of the air sparging period at the same sites. At Site SS-06, the second laboratory

vapor sample was collected during the period while the vapor extraction system was off (at the end of the sparging test), while at Site SS-08 Location B, the sparging system did not operate without the simultaneous operation of the soil vapor extraction system. The reason for the difference at the two sites was that an *in situ* respiration test was conducted at SS-06 and not at SS-08 Location B.

The laboratory samples were collected using summa canisters. The summa canisters were supplied by the laboratory with an initial vacuum of approximately 29 inches of mercury. Gas regulators were supplied by the laboratory with the flow rate set to allow the canisters to sample gas for approximately one hour. The initial vacuum in each canister was checked to verify full vacuum and the initial vacuums were recorded on the chain of custody. The regulators were connected to the sampling port using Teflon tubing supplied by the laboratory and Swageloc™ compression fittings.

For Site SS-06, the first sample was obtained from port 1 shown in Figure 2-1. The tubing was connected to the port and the valves to the port and to the summa canister were opened and the sampling continued for a period of one hour. A duplicate sample was also obtained from this same location simultaneously. The Teflon tubing was equipped with a "y" connector and the second canister was open during the same period of time. A third canister was opened to the atmosphere at Site SS-06 during the sampling period. This was used as an ambient blank. A fourth canister was sent back to the laboratory as a trip blank.

After one hour of sampling, each canister was closed and the final vacuum of each canister was measured and recorded on the chain of custody. The regulators were removed from the canisters, protective caps were installed and the canisters were shipped back to the laboratory for analysis.

For the second sampling at Site SS-06, only one summa canister was used. This canister was connected to the sampling port of well MP6. The procedure described above was used for preparation and sampling with this canister.

At Site SS-08 Location B, the procedure described above for Site SS-06 was followed for the first sampling, with the first summa canister and the duplicate attached to port 1 on the SVE pilot system (Figure 2-1). The same blanks and duplicates were used. However, for the second sampling (during sparging) the single summa canister was connected to port 1 on the SVE pilot system. The reason for the difference is that at SS-08 Location B, the air sparge system did not operate without the SVE system (as it did for approximately 11 hours at the end of the sparge test at Site SS-06).

3.6 AIR SPARGING TESTS

Following the completion of the extended constant rate vacuum extraction test at sites SS-06 and SS-08 Location B, the vacuum blower continued operation and a constant rate air sparge test was initiated. At Site SS-06 the air sparging test continued for a period of six days. At Site SS-08 Location B the air sparging test continued for eight days. Field sampling parameters were obtained from all groundwater monitoring wells listed in Section 2.3 prior to the start of the air sparging test. The same parameters were sampled daily during the sparging test and several times following the end of the sparging test. The groundwater sampling procedures and the procedures for conducting the air sparging tests are provided in the following subsections.

3.6.1 Groundwater Sampling Procedures

The monitoring wells were purged using a peristaltic pump. A length of polyethylene tubing was dedicated to each monitoring well. The tubing extended from the screened interval to the top of casing. While the wells were not being sampled, the tubing remained in the well about

one inch below the top of the casing. The casing was sealed using a threaded brass plug to prevent short circuiting of sparge air during the sparging test. At the time of sampling, the brass plug was removed and a second length of polyethylene tubing was attached to the dedicated tubing using a flexible silicone connector.

The second length of polyethylene tubing extended to the intake of the peristaltic pump. The outflow of the pump was connected to the lower inlet of a YSI 6000 sonde style flow cell with polyethylene tubing. The upper inlet to the flow cell was connected to polyethylene tubing extending to a water storage tank.

Groundwater from the monitoring wells was directed through the flow cell at a rate of approximately 0.15 gpm. As water flowed through the cell it flushed across analytical probes used for measuring dissolved oxygen (DO), oxidation reduction potential (ORP), pH, conductivity, salinity, temperature, and total dissolved solids. These measurements were displayed on a digital readout, which was recorded manually to data sheets.

Data recording started approximately two minutes after the flow cell filled with water from the given monitoring well. Each of the parameters were recorded on approximately 5 minute intervals until all of the readings reached a stable state. A minimum of three readings were recorded for each well and generally no more than five readings were recorded for each event. The final reading was considered the data point for the well for that sampling event. The intermediate values were recorded and maintained in the data sheets to verify the stability of the reading and to provide verification of adequate purging.

On three occasions, at both sites SS-06 and SS-08 Location B, laboratory samples were obtained for analysis of sulfur hexafluoride. To obtain these samples, the same purging and recording procedure was followed until steady state was attained. The sulfur hexafluoride sample was then obtained from the outflow side of the flow cell. Two 40 ml samples of water were taken without headspace. Latex gloves were worn during the sampling procedure. The

water was allowed to fill the vials with a minimum of agitation. The samples were placed in a cooler with ice and shipped to the laboratory for analysis.

3.6.2 Air Sparging Test Procedures

The air sparge (AS) pilot testing system was connected to the helium and sulfur hexafluoride supply tanks and to the sparge well as described in Section 2.2. Prior to the start off the test, the AS pilot system was tested to verify the proper operation of the gauges and to verify the proper helium flow rate to provide approximately 2 percent helium to the sparge air stream.

Following initial checks, the sparge system was connected to well S1 and the sparging test was initiated. The air sparging began with constant rate sparging at an air flow rate of approximately 22 standard cubic feet per minute (scfm). The sparge air contained just under two percent helium and approximately 0.3 percent sulfur hexafluoride. The flow rates of helium and sulfur hexafluoride were maintained by monitoring the respective flow meters and adjusting a needle valve on the flow meter to maintain a constant flow rate. The flow rate of the sparge air to the formation required little adjustment as a constant rate was maintained by the blower as periodically recorded form the flow meter.

At Site SS-06, the initial constant rate sparging test was continued for 24 hours. A series of pulsed rate intervals followed. The series included, in order, the following pulse sequences: (1) 8 minutes sparging and 2 minutes off, (2) 6 minutes sparging 4 minutes off, and (3) 5 minutes sparging and 5 minutes off. Each pulse rate interval was continued for approximately 24 hours. The pulse rate series was followed by 24 hours of constant rate sparging which concluded the test.

At Site SS-08 Location B, the initial constant rate sparging test was continued for the first three days of the sparge test. The pulsed rate sparge test then began with a pulsing rate of five

minutes on and five minutes off. This pulsed rate sparging then continued for the remaining four days of the sparge test.

The concentration of VOCs in the soil gas extracted by the pilot SVE system was measured periodically from two system ports (ports 1 and 4) while the SVE pilot test system was in operation. Soil gas parameters were also measured in the vapor monitoring wells during the air sparging tests as described in Section 3.3. Of particular interest for the sparging tests were any changes in soil gas constituents in the extracted vapor that could be attributed to air sparging. The detection of helium at a given vadose zone monitoring well (while the pilot SVE system was in operation) provided reasonably good evidence that the sparge air had surfaced in the vadose zone at a location downgradient of the given monitoring well.

Increases in volatile constituents in the vapor monitoring wells or the extracted vapor stream also provide indication of the effects of air sparging and can be used in some instances to evaluate the distance of sparging influence.

Sulfur hexafluoride was not analyzed in the vadose zone primarily due to the relative expense of sulfur hexafluoride analysis in comparison to helium detection. Helium provided a less expensive monitoring tool in the vadose zone with similar expected results.

Soil gas samples were collected for laboratory analysis of volatiles as described in Section 3.4. The comparison of volatile constituents in samples taken prior to the start of the air sparging with those taken near the end of the air sparging provides some measure of the effectiveness of the sparge system at removing volatile constituents from groundwater. This comparison can be made for Site SS-08 Location B where the summa canister samples were obtained from the extracted vapor stream prior to the start of the air sparging test and near the end of the air sparging test. For Site SS-06 a different sampling procedure was employed. At this site, it was considered more important to determine the constituents of the sparge air without vapor extraction, to evaluate the potential for venting the sparge vapors without vapor extraction.

The first vapor sample at Site SS-06 was used as a base line for the soil vapor concentration with only soil vapor extraction. The second sample was obtained after the final 10 hours of sparging when the vapor extraction system had been shut off.

After ending the sparging tests at both sites, follow-up measurement of field parameters in the groundwater and vapor monitoring wells continued for three days at Site SS-08 Location B and for a total of 19 days at Site SS-06. The greater follow-up sampling period at Site SS-06 was completed to provide a measure of biological activity as a part of the *in situ* respiration test described below.

3.7 IN-SITU RESPIRATION TESTING

The pilot testing was designed to determine if vadose zone biodegradation of volatiles emitted by air sparging was sufficient to permit the discharge of vapors to the atmosphere without collection and treatment. An *in situ* respiration test performed at SS-06 provided information about the effectiveness of vadose zone biodegradation.

3.7.1 Test Methods

The SVE pilot test and the AS pilot test were performed at Site SS-06 as described above in Sections 3.5 and 3.6. Near the end of the soil vapor extraction test, the SVE pilot system was shut off and the sparge air was allowed to discharge and accumulate in the vadose zone. As in the previous portions of the test, helium was added to the sparge air as a conservative tracer.

The sparge air was then allowed to accumulate in the vadose zone for approximately 11 hours of sparge operation without the SVE blowers. The sparge air moved to most vapor monitoring well locations as evidenced by the accumulation of significant concentrations of helium, methane and volatiles in the vadose zone at these locations.

The sparge system was then shut off and the rate of oxygen decline, the rate of carbon dioxide accumulation, the rate of methane decline, the rate of helium decline, and the changes in volatile concentrations in the vadose zone were monitored over a 19 day period following the end of the sparge test.

The rate of return of the groundwater to an anaerobic state was also measured (with DO and ORP readings) over the same period to provide a rough indication of the upper limit for the potential biological degradation rate in the vadose zone.

3.7.2 Test Analysis

A measure of the rate of accumulation of soil gas constituents can be used as a measure of the expected concentration of soil gas constituents that will be generated from a sparging system after a short period of operation. This rate was estimated in several ways. First, the data from the period of sparge operation with the vapor extraction system were analyzed to try to establish a rate of volatiles production that can be attributed to air sparging. In addition, the rate of accumulation of volatile constituents in the vadose zone gas following the end of the vapor extraction was estimated from the soil gas data obtained in the vadose zone monitoring wells. Finally, the concentration and nature of volatile constituents in the sparge air in the vicinity of the sparge well was determined based on the soil gas sample that was analyzed in the laboratory for volatile organic soil gas constituents.

The rate of production of volatile organic soil gas constituents by the air sparge system can be compared to the rate of destruction of these constituents by vadose zone microbial action to provide a rough estimate of the likelihood that biological degradation can degrade volatile constituents at a rate sufficient to prevent significant volatile release to the atmosphere.

The rate of biological degradation of volatile organic constituents in the vadose zone was measured by plotting the rate of oxygen decline at the soil vapor monitoring wells. The oxygen decline was observed over the 19 day period and the rate of decline was quantified for the initial linear portion of the plots.

A similar test was originally planned for Site SS-08 Location B. However, the initial soil gas samples at this site indicated little or no vadose zone contamination (near atmospheric oxygen levels), and extracted vapor before and after the initiation of sparging additionally indicated little or no groundwater contamination with volatile organic constituents at this location. Therefore, the high oxygen levels present at the end of the SVE and AS pilot tests differed only marginally from the pretest conditions, and a measure of biological degradation potential would not have been possible.

3.8 MODELING AIR FLOW

The primary objective of the SVE pilot test was to determine the optimal spacing and flow rates for a vapor extraction system that would capture the air generated by an air sparging system. To achieve this objective several types of vapor extraction (and injection) tests were performed at each site and were analyzed by a variety of analytical procedures. The results are expected to provide approximations of the air permeability of the formation and an approximation of the required spacing and flow rate for a full scale vapor extraction system.

In reality, the calculation of air permeability provides limited information about spacing and flow rate requirements for a full scale system without additional modeling utilizing the calculated values. The modeling can be numerical or analytical depending on the needs and constraints of the project.

In addition, the analytical methods used to calculate air permeability all have limitations. In general, the models consider only one-dimensional radial flow to the extraction well even when

vertical leakage from the surface is allowed as in the transient analyses described above. The type curve method utilizing a leaky well function is probably the most sensitive of the analytical procedures employed, but it can not make use of the advantage of having data collected at different levels with partially penetrating observation wells. Instead, an averaging of the air permeability calculations at three depths (or two depths at SS-08) must be made to approximate the conditions assumed by the analytical model.

A numerical flow model was used for two purposes in this analysis. The first was to be able to extend the vacuum step test results beyond the point allowed by the pilot test equipment. It is desirable to extend a vacuum step test to the point where a plateau is reached where increasing the vacuum results in no additional air flow or results in less air flow. This phenomenon is caused by the rise in the water table at each increase in vacuum.

The second way that a numerical model was used in this analysis was to provide a means to calculate the radius of influence for a single vacuum extraction well in the formations tested. The calculation of the air permeability of the formation is of limited value if this information is not modeled to establish the expected effects of a vacuum extraction well given the permeability, porosity, and other factors determined with the analytical techniques.

The numerical flow model chosen for use in this project was MODFLOW. This choice was based on the wide acceptance of this model for groundwater flow applications, the ready availability of quality pre and post processors for this model, and the flexibility of this model for analyzing the existing data set and for testing various spacing and flow rate options for the full scale remediation system.

The use of groundwater flow models to simulate subsurface air flow has been well established in the literature. Massmann (1989) looked at the potential for using groundwater flow models to simulate air flow and determined that such models were appropriate provided that the applied vacuum was less than about 0.2 atmospheres.

The theoretical basis for the use of a finite difference numerical flow model, such as MODFLOW is developed as follows:

The governing equation for three dimensional flow solved by a finite difference method is provided in Equation 9.

$$S_s \frac{\partial h}{\partial t} = -\frac{\partial q_x}{\partial x} - \frac{\partial q_y}{\partial y} - \frac{\partial q_z}{\partial z} \qquad \text{Equation 9}$$

where: the volumetric flux density in the i^{th} direction is given by:

$$q_i = -K_i \frac{\partial h}{\partial x_i} \qquad \text{Equation 10}$$

and where: S_s = specific storage of the aquifer

q_i = the volumetric flux density in the i^{th} direction

K_i = the conductivity of the aquifer

h = the potentiometric head

t = time

These equations describe groundwater flow in an aquifer subject to certain assumptions regarding the decoupling between saturated and unsaturated zones. The same equations can be used to model gas flow given the following assumptions:

1. The gradients in the gas phase density are small in comparison to the divergence in the gas velocity.
2. The effects of gas pressure gradients on water flow by capillary effects are disregarded (water table upwelling is ignored).

3. Gravitational gas flow is assumed negligible in comparison to pressure effects.

These assumptions should be met by the low vacuum application proposed here. The assumption of no upwelling of the water table does not have to be met. Water table upwelling can be simulated in MODFLOW by applying the upwelling manually. Given the above assumptions, Equations 9 and 10 will describe gas flow in the vadose zone when q_i is taken as the volumetric flux density of the gas and other variables are defined as follows:

$$h = \frac{P}{\rho_w g} \qquad \text{Equation 11}$$

$$K_i = \frac{\rho_w g k_{ai}}{\mu_a} \qquad \text{Equation 12}$$

$$S_a = \frac{m_a \rho_w g n_a}{\rho_a RT} \qquad \text{Equation 13}$$

where:

h = gas pressure head expressed in equivalent height of water (L)

K_i = the gas conductivity in the i^{th} direction (L/T)

S_a = specific storage of the gas

P = the absolute gas phase pressure (M/LT^2)

ρ_w = density of water (M/L^3)

g = acceleration of gravity (L/T^2)

k_{ai} = gas permeability in the i^{th} direction (L^2)

μ_a = dynamic viscosity of the gas (M/LT)

m_a = molecular weight of the gas (M/mole)

n_a = gas filled porosity (L^3/L^3)

ρ_a = density of the gas (M/L^3)

R = universal gas constant ($M\ L^2/T^2$ mole K)

T = temperature in degrees Kelvin (K)

When the above equations are used to determine the parameters to input into MODFLOW, air permeability in the subsurface can be simulated.

To set up the MODFLOW model it was also necessary to define the boundary conditions. The ground surface was set as a constant head boundary with the head being equal to the elevation of the ground surface above the water table (units of feet were used in the model). Because the presence of significant horizontal gradients in the vadose zone is unlikely, the horizontal boundary conditions were set as constant heads also with the same head as the layer at the ground surface. The horizontal boundaries were placed far enough away from the areas to be modeled to provide no recognizable influence. The lower boundary was a no-flow boundary to represent the water table (where no air leakage can occur).

The numerical model was also be used as an independent method for establishing formation air permeability and other qualities. The model allowed the use of partial penetration data, such as was available from the pilot tests, to better define soil parameters. The model was also used to evaluate capture of sparge air by the vacuum extraction system to provide a greater level of confidence in the required well spacings. However, the relationship between air flow rate at extraction wells and the required extraction well spacing was not examined in this analysis. Optimization of this type could be performed as a part of the system design and the results may provide a lower overall cost for system installation and operation.

4.0 RESULTS AND DISCUSSION FOR SITE SS-06

The air permeability testing, long term vapor extraction pilot test, air sparging pilot test, and *in situ* respiration tests were conducted between November 12, 1997 and December 13,1997. The results of these tests are presented and discussed in the following subsections. A summary table of the SVE pilot system and AS pilot system operational data for Site SS-06 testing is provided in Appendix B.

Frozen soil or snow?

4.1 AIR PERMEABILITY

Short term transient and short term steady state air permeability tests were conducted at Site SS-06. Details of the pilot testing system and the extraction and observation wells are provided in Section 2 and details of the methods used to conduct and analyze the tests are included in Section 3. The results of the air permeability testing are presented here.

Steady state data were collected from each of the monitoring wells at several times following the start of vacuum extraction. Table 4-1 provides the vacuum results from the steady state test. It was determined that steady state was reached very early in the test. Significant increasing trends in vacuum did not occur in any of the wells after the first reading, taken at 15 minutes into the test. Thus, any of the data collection times listed in Table 4-1 were acceptable for the calculation of steady state permeability.

Three analytical methods were used to calculate air permeability from the steady state data: the effective radius method, the two well steady state method, and the two well pseudo steady state method. The input data and the resulting calculated values of permeability for each method are summarized in tables in Appendix B. Example calculations for each method are also included in Appendix B.

TABLE 4-1
STEADY STATE VACUUM TEST RESULTS
SITE SS-06
WURTSMITH AFB, MICHIGAN

	11/13/97 16:15	11/13/97 17:04	11/13/97 17:52	11/13/97 21:55	11/14/97 9:20
MP6	17.75*	17.74	17.75	18.08	18.03
MP1A	2.57	2.55	2.53	2.54	2.48
MP1B	5.80	5.72	5.65	5.69	5.56
MP1C	6.78	6.70	6.63	6.74	6.61
MP2A	1.12	1.13	1.07	1.09	1.11
MP2B	1.43	1.42	1.36	1.41	1.40
MP2C	2.60	2.58	2.52	2.60	2.58
MP3A	1.02	1.01	0.96	1.01	1.00
MP3B	1.89	1.87	1.85	1.88	1.86
MP3C	2.71	2.70	2.67	2.70	2.69
MP4A	0.31	0.35	0.31	0.31	0.30
MP4B	0.80	0.84	0.77	0.76	0.78
MP4C	1.54	1.58	1.51	1.52	1.56
MP5A	0.06	0.10	0.09	0.09	0.10
MP5B	0.27	0.31	0.28	0.29	0.30
MP5C	0.67	0.69	0.67	0.69	0.64

Test start time = 11/13/97 at 16:00

Flow Rate = 154 scfm

* all values reported in inches of water column vacuum

The effective radius method also required an estimation of the effective radius of vacuum influence for the test. As discussed in Section 3, this was estimated using a distance-drawdown plot. The effective radius determined from this method was 54 feet. The distance drawdown plots used to calculate this distance are included in Appendix B.

Analysis of the transient test data involved type curve matches between the transient data (plotted as log-log) and the Hantush-Jacob leaky confined type curves. The data plots for each test are included in Appendix B, and the type curves are shown in Figure 3-2.

Table 4-2 presents an overall summary of the air permeability results from the steady state and transient methods used to analyze the test data. Some of the values presented in Table 4-2 were averaged from values obtained by the analytical methods. The actual results for each analysis conducted are provided in Appendix B. Calculated permeability values vary from a low of 7.5 darcys to a high of 155 darcys with an overall average of 60.7 darcys. This represents greater than one order of magnitude variation within the wells and methods tested.

The method that calculated the highest average air permeability values was the steady state effective radius method. The lowest values were calculated for the pseudo steady state method. The general trend for the tests of each type was for higher calculated permeability values for greater distances from the vapor extraction well. This trend is not considered to be a real permeability trend in the formation, but a result of the analytical methods used. The change with distance is likely a result of the fact that none of the methods include the effects of three dimensional flow that will result from the leakage of air into the formation from the ground surface.

The problems associated with the assumption of one dimensional flow are perhaps most evident with the transient tests. The results of the transient permeability tests (provided in Appendix B) indicate a clear trend toward lower calculated permeability with increasing depth of the observation well. The trend toward higher permeability with distance is also very evident in

TABLE 4-2
SUMMARY OF ANALYTICAL SOIL PERMEABILITY CALCULATIONS
SITE SS-06
WURTSMITH AFB, MICHIGAN

	Steady State Effective Radius Method (darcys)	Steady State Two Well Method (darcys)	Pseudo Steady State Method (darcys)	Transient Type Curve Method (darcys)	Average (darcys)
MP1	59.8	46.8	7.5	21.6	33.9
MP2	97.2	74.2	15.1	-	62.1
MP3	86.8	64.5	10.3	38.8	50.1
MP4	105.8	78.2	12.4	155.0	87.9
MP5	106.4	84.7	15.9	63.9	67.7
Average	91.2	69.6	12.2	69.8	60.7

the transient solutions. Although the transient solution does incorporate air leakage into the formation from the soil surface, it still assumes horizontal, one-dimensional flow. As evidenced by the calculated values of permeability and by the data showing much higher vacuum values at depth, the assumption of horizontal flow is not well justified at this site.

A numerical model was used as a last step in estimating the soil permeability characteristics at this site. The results of the transient leaky analytical model were used as a starting point for the numerical model. The numerical finite difference model MODFLOW was used for this analysis as described in Section 3. Model runs were completed and compared to steady state data for each vadose zone monitoring well (at each level). The model allowed a better use of the available data and allowed incorporation of three dimensional flow to the vapor extraction well.

The model was run and permeability values for the vadose zone and the surface soil were adjusted until a best fit with the field data was obtained. The fit provided by the model was considerably better at all locations than the fit provided by any of the analytical methods. The best fit was attained using a horizontal air permeability of 50 darcies, a vertical air permeability of 17.7 darcies and a surface layer vertical and horizontal air permeability of 17.7 darcies (on foot thick surface layer). Areas of the site that were covered by less permeable materials such as the road and the parking lot were given a lower surface layer permeability in the model. The horizontal air permeability value determined for the model was within the range of values determined using the analytical methods and was relatively close to the overall average of the values obtained by the various analytical methods (60.4 darcies).

4.2 VACUUM/FLOW RATE CORRELATION

A vacuum step test was conducted for Site SS-06 as described in Section 3. The test was conducted by increasing vacuum up to the maximum rate and vacuum possible with the pilot test equipment. The test was then stepped back down to zero vacuum. The results of the test

are plotted on Figure 4-1. The legend on Figure 4-1 shows whether the data are from the step up or step down portion of the test. A data table listing the results of the step test is included in Appendix B.

The step test data show a nearly straight linear trend of vacuum versus air flow rate. The specific yield for the well calculated from this test is approximately 8 scfm per inch of water column vacuum applied. Stated in terms of vadose zone thickness, this yield is approximately 0.37 scfm per inch water column vacuum per foot of unsaturated formation.

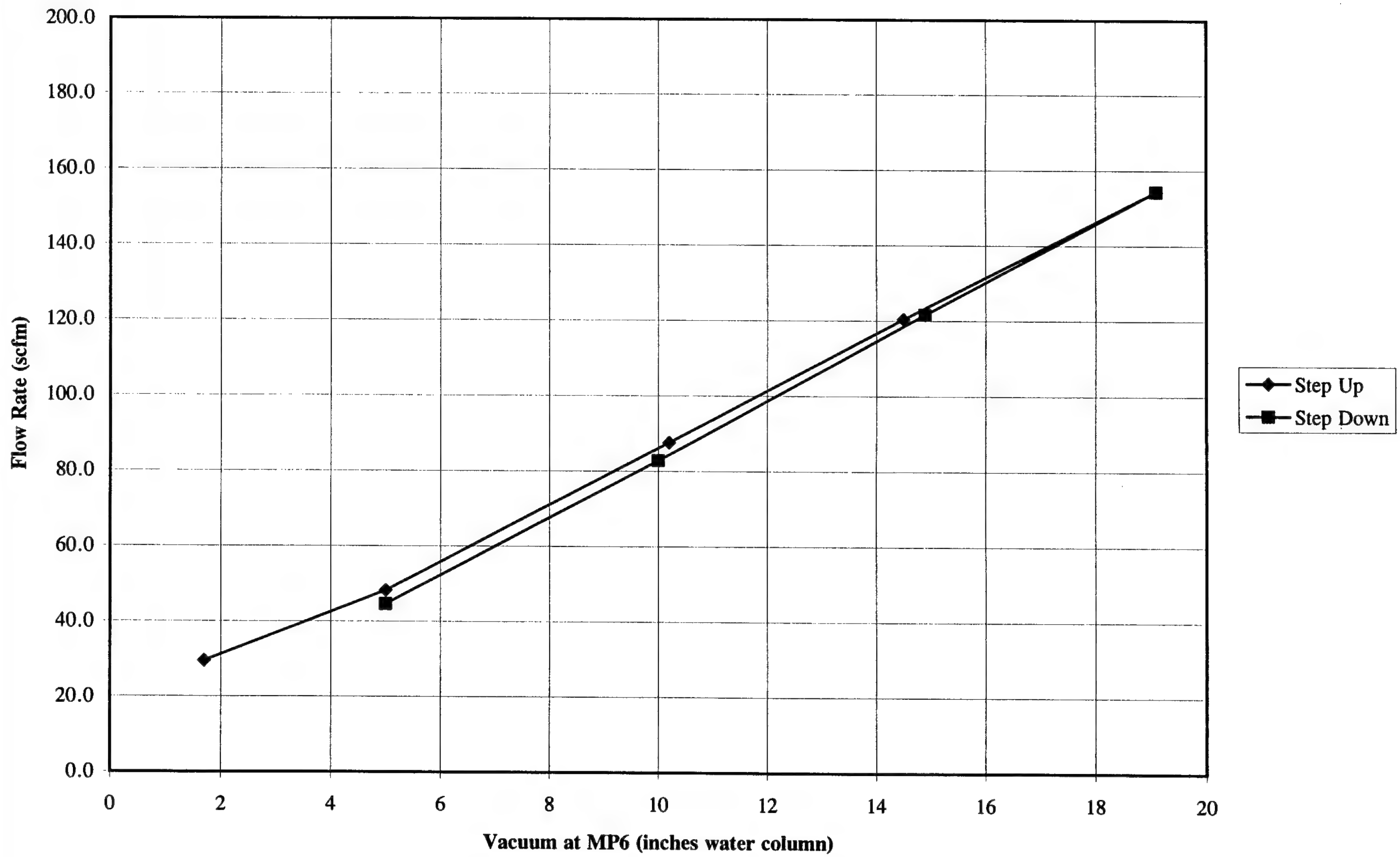
A numerical model was used to extend the vacuum versus flow rate relation curve to higher vacuums than were possible with the pilot test equipment. The extended curve indicated a decline in flow rate after reaching approximately 350 scfm. The design flow rate per vacuum well was chosen at 300 scfm, based on these results.

No data supporting 300 scfm

4.3 AIR SPARGING TEST

Air sparging tests were conducted at Site SS-06 using the air sparging pilot test equipment discussed in Section 2 and according to the methods detailed in Section 3. The results of the sparging tests and a discussion of those results are provided below. The most important determinations for this test was the radius of influence for the sparge well and the depth of sparging influence in the aquifer. Other factors considered were the effects of sparging on volatiles in the vadose zone, the effects of pulsing the sparge system, and the effects of sparging on other water chemistry parameters. These effects were established in the test by observing changes in the concentration of dissolved oxygen, changes in ORP, the presence of helium at specific locations in the vadose zone, the presence of sulfur hexafluoride in groundwater, and changes in these parameters occurring after the end of the sparging. The test results are discussed in terms of these indicator parameters in the following subsections.

FIGURE 4-1
VACUUM STEP TEST
SITE SS-06
WURTSMITH AFB, MICHIGAN



4.3.1 Dissolved Oxygen Results

Dissolved oxygen is a primary indicator parameter for the performance of an air sparging system. As sparge air is released into the aquifer it travels through the saturated zone in air phase channels. These channels are in contact with water coated aquifer material and groundwater at the margins of the channels. The contact between air and groundwater allows exchange of oxygen to the aquifer and volatile organic constituents to the air stream. As a result, areas of the aquifer which are effected by sparging typically show an increase in dissolved oxygen content.

Dissolved oxygen concentration of groundwater at each of the groundwater monitoring wells was determined approximately daily through a period extending from before the start of the sparging test until 19 days after the sparging had ended. The frequency of testing declined in the period after the end of sparging, and longer term testing was primarily for the purpose of the *in situ* respiration test (described below). The dissolved oxygen content of groundwater was plotted over this time period for each monitoring well to aid in determining if groundwater in the location of a given well had been effected by the sparging.

Figure 4-2 is a plot of dissolved oxygen for well MP2D. The initial level of dissolved oxygen at this well was less than 1 mg/L. After the start of the sparging test, the dissolved oxygen concentration in the well increased rapidly to greater than 2.5 mg/L. The dissolved oxygen concentration declined slightly during the second and third days of sparging when pulsed sparging was occurring, but increased again to greater than 4.5 mg/L during the day of 50 percent pulsed sparging (one half time off). Air sparging ended on November 24, and the oxygen level generally declined after this time to approximately 0.5 mg/ L on November 30.

Plots of dissolved oxygen levels at each of the other monitoring wells are included in Appendix B. Table 4-3 summarizes the results of these plots. All groundwater monitoring wells showed an increase in dissolved oxygen during and/or following the air sparging. The

FIGURE 4-2
DISSOLVED OXYGEN CONCENTRATION FOR WELL MP2D
SITE SS06
WURTSMITH AFB, MICHIGAN

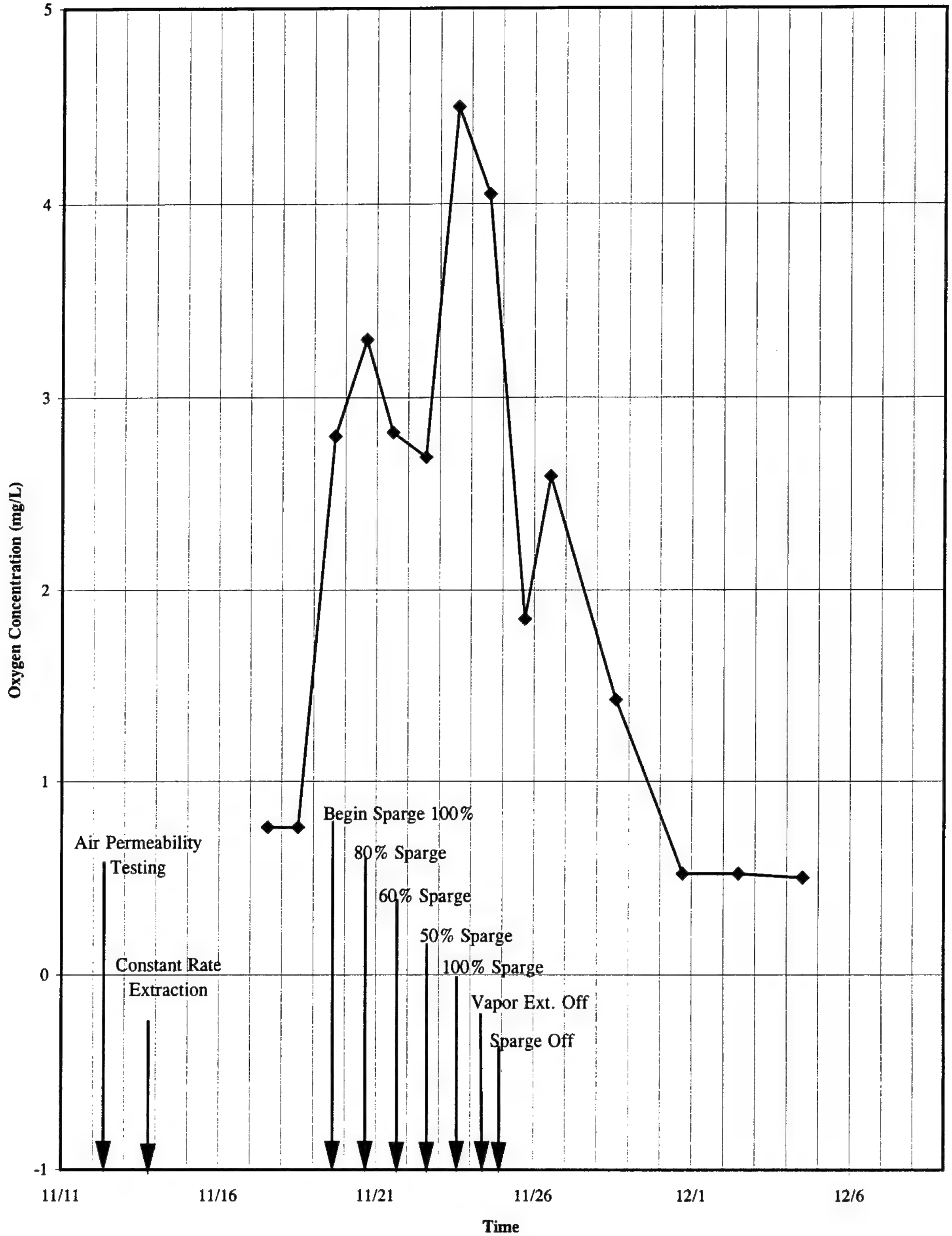


TABLE 4-3
SUMMARY OF DISSOLVED OXYGEN RESULTS
SITE SS-06
WURTSMITH AFB, MICHIGAN

	Initial DO (mg/L)	Highest DO During Test (mg/L)	Highest DO Following Test (mg/L)	Lowest DO Following Peak (mg/L)
MP1D	0.65	4.21	1.36	0.5
MP1E	0.43	6.8	2.61	0.52
MP1F	0.3	1.74	6.18	5.83
MP2D	0.76	4.5	2.59	0.5
MP2E	0.39	4.01	4.48	0.53
MP2F	0.37	0.74	1.85	0.41
MP3D	0.55	3.91	2.03	0.41
MP3E	0.42	6.16	1.97	0.5
MP4D	0.62	1.05	2.45	0.54
MP4E	0.37	0.9	2.19	0.43
MP5D	0.62	1.26	4.06	0.58
MP5E	0.51	1.03	4.35	0.5

general trend was similar to the trend exhibited in Figure 4-2, although the deeper wells tended to have more delayed increases in dissolved oxygen. The extreme case of this was well MP1F, which had its peak dissolved oxygen concentration on December 2, eight days after the end of sparging. All of the wells, except well MP1F, returned to near anaerobic conditions during the period of monitoring. These data clearly indicate that air sparging was successful at moving oxygen to each monitoring well location, for distances of at least 40 feet from the sparge well.

The evaluation of the effect of pulsed sparging is not as clear. Some wells showed a leveling in the dissolved oxygen content during the early part of the pulsed sparging similar to well MP2D, as shown in Figure 4-2 (wells MP1D, MP3D, and MP3E). During this period the sparging was changed from continuous to eight minutes on and two minutes off and to six minutes on four minutes off. These wells all showed increases in dissolved oxygen when the rate was decreased to five minutes on and five minutes off. The remaining wells showed some delay in the increases in dissolved oxygen. Although delayed, the increases tended to be gradual and steady (No indication of differences due to the pulsed sparging strategy is apparent in the data of these wells).

It is likely that the wells which exhibited delayed increases in dissolved oxygen did not fall close to an air channel formed by the sparging. However, an air channel was apparently close enough to the each of these wells to allow an increase in dissolved oxygen as oxygen diffused through the aquifer and was redistributed.

The wells that were apparently closer to air channels responded more quickly to the sparging and to changes in the sparging methods. These wells are the better indicators of the effects of pulsing, but they do not provide a clear picture of these effects. The gradual decline in oxygen levels in these wells during the first two days of pulsed sparging would suggest that pulsed sparging was less successful than continuous sparging. However, the increase in all of the

wells that occurred in during the day of pulsing at 50 percent may indicate that a longer off cycle in the pulsed sparging may be more effective.

4.3.2 Oxidation-Reduction Potential Results

The oxidation-reduction potential (ORP) of groundwater is a measure of the relative redox potential of the groundwater. Highly oxygenated groundwater will have a relatively high positive ORP. Groundwater in which biodegradation has removed oxygen (and other high potential redox couples) tends to have a low ORP (more negative). The background conditions in groundwater at Site SS-06 were of low ORP within the range of -47 to -135 mV. This is a relatively low ORP and is an indication of biological activity in breaking down the hydrocarbon contamination.

The general trend in the background ORP data was toward decreasing ORP with depth. This is probably due to the movement of oxygen from the vadose zone to groundwater, and the consumption of this oxygen near the water table surface by aerobic of facultative aerobic microorganisms. Deeper areas of groundwater not in contact with the vadose zone tend to have a lower ORP.

As air sparging brings oxygen to the groundwater, the ORP of the groundwater should increase. Thus, ORP is an additional parameter that can be used to determine if air sparging is influencing a given zone. It is conceivable that oxygen introduced to groundwater by sparging could undergo rapid enough consumption by the physical, chemical, and microbial oxygen demand of the groundwater that it may not be detected as dissolved oxygen during monitoring. In these cases, it is likely that some increase in the groundwater ORP would still be observed.

Time series plots of ORP for each monitoring well are included in Appendix B. Figure 4-3 is an example of these plots for well MP2D. This figure shows a similar trend in ORP to the

trend observed in dissolved oxygen for this well. The ORP increased steadily through the duration of the test, and declined slightly on the last day of the test. After air sparging ended, the ORP declined relatively steadily to pretest levels. It appears that the ORP was increasing prior to the start of sparging. This is probably the result of oxygen entry into the upper portion of the aquifer from the vadose zone that had become oxygenated by the soil vapor extraction pilot test.

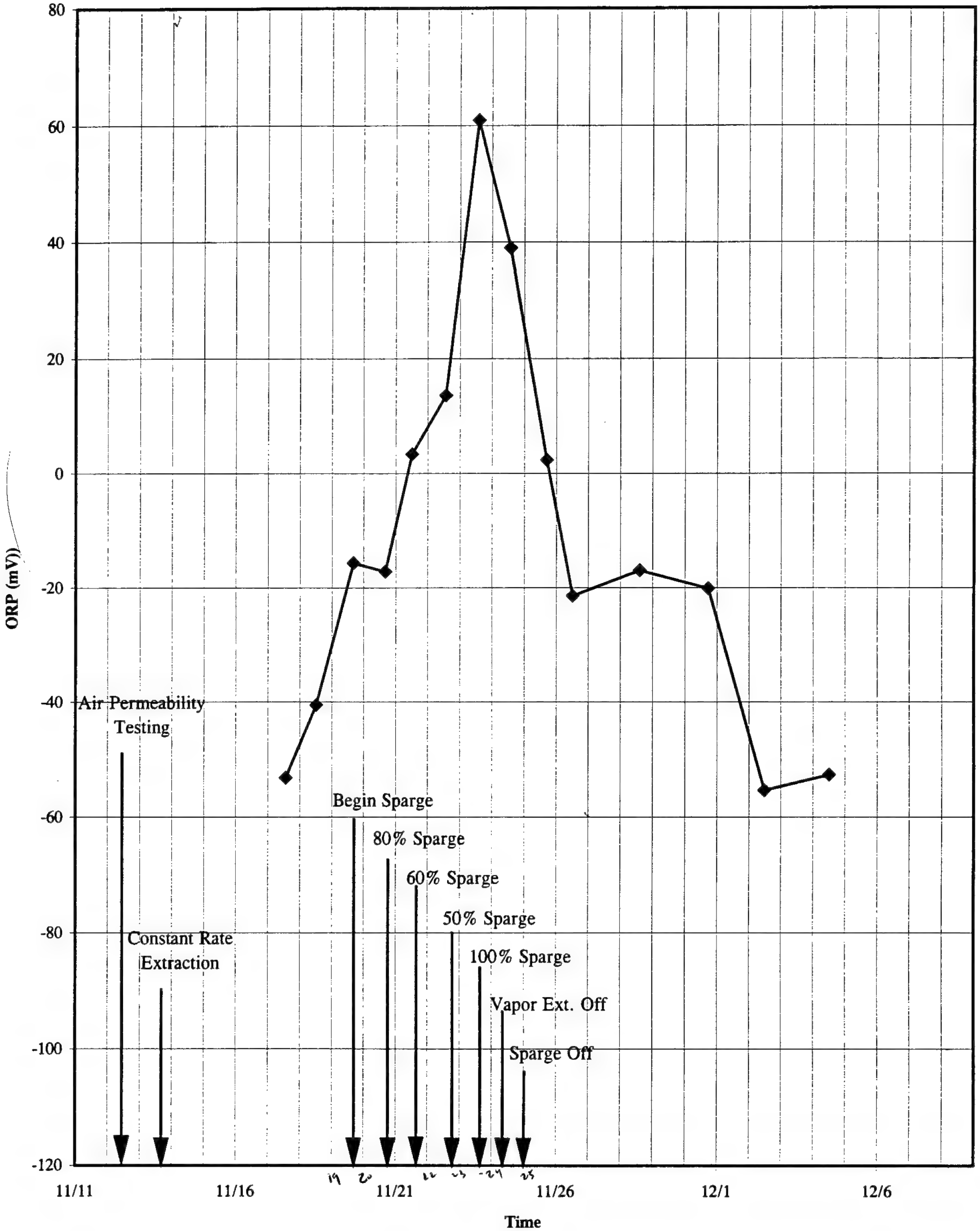
In general, the ORP values collected for this test are less consistent than the dissolved oxygen results, and the ORP was frequently observed to fluctuate during the tests. It is likely that some mixing of groundwater occurred as a result of the air sparging, and this mixing may have resulted in fluctuations in groundwater ORP at a given location.

Overall, the trends in the ORP data were similar to the trends in dissolved oxygen data. The ORP increased during the testing and decreased following the end of the tests. The ORP data provide corroboration of the dissolved oxygen data for determination of the extent of the sparging influence, but the data provide no additional information regarding the effectiveness of pulsed sparging.

4.3.3 Helium Results

Helium was included as a conservative tracer in the sparge air as discussed in Section 3. Helium does not dissolve to a great extent in the groundwater and should not interact with aquifer materials. It can be used as an additional measure of the distance that sparge air has traveled away from the sparge well. This determination is only possible if vacuum extraction, at a rate significantly higher than the sparge rate, is continued near the sparge well while the test is in progress.

FIGURE 4-3
OXIDATION-REDUCTION POTENTIAL FOR WELL MP2D
SITE SS-06
WURTSMITH AFB, MICHIGAN



If vacuum extraction is not present, helium moves away from the sparge area through the vadose zone and can be detected at great distances from the sparge well regardless of how far the sparge air traveled through the aquifer. With a vacuum system providing capture within the vadose zone surrounding the sparge well, sparge air that crosses into the vadose zone from the aquifer tends to move back toward the extraction well, which is located adjacent to the sparge well. Under these conditions, the detection of helium at a vadose zone monitoring well is an indication that the sparge air moved within the aquifer to a point further than the given monitoring well, and is moving back to the extraction well through the vadose zone.

Helium was detected in five monitoring wells during the period prior to the end of vapor extraction. These wells included all of the C level wells at the site (MP1C, MP2C, MP3C, MP4C, and MP5C). Helium was not found at any of the B level and A level wells while the vapor extraction system was running. The detection of helium only at the lower wells is expected and confirms the use of helium data to aid in determining the radius of influence for air sparging. The expected air flow in the aquifer would be horizontal and radial toward the extraction well. Any vertical flow should be in a downward direction where air leaking from the surface enters the flow system. Therefore, sparge air entering the vadose zone from the aquifer would travel horizontally back toward the vapor extraction well, and should only be detected in the lower level wells.

The detection of helium in all the lower level wells indicates relatively good distribution of the sparge air to locations beyond these wells. The detection of helium at the most distant level C well (MP5C), is an indication that air is traveling further than 40 feet from the sparge well within the aquifer (at least in the direction of MP5).

The helium recovery rate for this test was relatively high. The average rate of helium injection into the sparge air during the last three days of the AS/SVE test was 1.6 percent. The average concentration of recovered helium during the same period was 0.28 percent. Given the average vacuum extraction flow rate during this period of 93.8 scfm and the injection rate by

the sparge system of 22.1 scfm, the helium flow into the aquifer was 0.354 cfm and the helium capture by the extraction system was 0.263 cfm. This represents a capture efficiency of 72.4 percent.

4.3.4 Sulfur Hexafluoride Results

Sulfur hexafluoride was used as an additional conservative tracer in the sparge air. Sulfur hexafluoride dissolves in groundwater to a somewhat greater degree than oxygen. Once dissolved in groundwater, it provides a good indication that sparge air was present at a given location. It does not interact with aquifer materials and it is not degradable within the aquifer. In addition, sulfur hexafluoride can be detected at very low concentrations.

Sulfur hexafluoride was injected into the sparge air at a concentration of approximately 0.3 percent. The equipment and methods for sulfur hexafluoride injection and the methods used for sampling are discussed in Sections 2 and 3. Samples for sulfur hexafluoride analysis were taken three days after sparging began, just before the end of the air injection period, and again, four days after the end of the air sparging test. The results of the sulfur hexafluoride analyses are provided in Table 4-4. Sulfur hexafluoride was detected at all well locations at all sample times.

The highest concentrations of sulfur hexafluoride were found in wells within the MP1, MP2, and MP3 clusters, although the first sample collected at MP5D also showed a relatively high sulfur hexafluoride concentration. No clear trend is present with time in the wells (i.e. the concentrations did not appear to increase with time). In some cases the concentrations declined with time. The data suggest that sparge air was present at each of the locations tested, and that the proximity of sparge air to a given location probably varied during the course of the test. This result is consistent with the concept of random movement of sparge air in the subsurface and the probable frequent changes in air channel locations within the aquifer.

TABLE 4-4
SULFUR HEXAFLUORIDE ANALYTICAL RESULTS
SITE SS06
WURTSMITH AFB, MICHIGAN

Well	11/22/97 SF6 (μg/L)	11/24/97 SF6 (μg/L)	11/28/97 SF6 (μg/L)
MP1D	1600	660	1200
MP1E	1500	1600	4700
MP1F	5400	1500	3300
MP2D	5100	3800	1700
MP2E	5500	1500	2600
MP2F	3300	1200	810
MP3D	3600	1200	2000
MP3E	4000	2400	4800
MP4D	990	680	1000
MP4E	98	1300	460
MP5D	3300	76	91
MP5E	450	18	13

Sparging test began on 11/19/97 at 13:50 (constant rate sparging)
Pulsed sparging began on 11/20/97 at 14:08
Sparging ended on 11/24/97 at 21:30

4.3.5 Sparging Radius of Influence

The methods used to determine the presence of sparge air within the aquifer suggest that air sparging was effective in all of the locations monitored. The most distant wells exhibited all of the characteristics of sparge influence, and all wells exhibited sparge influence regardless of depth in the aquifer or angular orientation around the sparge well.

Based on these results it is concluded that sparging should be effective in this location up to a radius of 40 feet from the sparge well. It is likely that some sparge influence is present beyond 40 feet, but this can not be quantified using the data collected for this test and sparge influence is likely to become more spotty with distance from the sparge well. To achieve good coverage with sparge air, the grid of sparging wells should be spaced 60 feet on center. This will allow some overlap of sparging influence in most areas. In reality, sparging tends to be irregular in the margins of extent, and it is generally not possible to assess whether complete coverage is occurring. The data obtained from this test suggest that sparging should be effective at delivering dissolved oxygen to the groundwater for biodegradation within the proposed spacing and at delivering air flow for stripping volatiles in some locations.

4.4 *IN-SITU* RESPIRATION TEST RESULTS

The *in situ* respiration test essentially began when the vacuum extraction blower was shut off on 11/24/97. The sparge system operated for a period of 11 hours after the vapor extraction system was shut off. The result of the sparge-only period was the production of a large volume of soil gas with near injection levels of oxygen and helium plus methane and VOCs that had been stripped from groundwater or generated in the vadose zone. The purpose of the in situ respiration test was to determine if biological degradation of volatiles generated by the sparge system could provide enough degradation so that a vapor collection system would not

be necessary. The conditions present in the vadose zone at the end of the sparge-only period provided the starting point for this determination.

Two types of evidence are required for making this determination: (1) the expected rate of volatiles production from sparging and (2) the expected rate of biological degradation. The expected rate of volatiles production was estimated based on the data generated during the sparge-only period. The expected rate of biological degradation was evaluated from the *in situ* respiration test conducted following the end of air sparging.

4.4.1 Rate of Volatiles Production

Soil gas concentration data for oxygen, carbon dioxide, methane, helium, and VOCs are presented in tables in Appendix B, and plots of soil gas oxygen, carbon dioxide, methane, and helium for each vadose zone well are also included in Appendix B. The instrument reading of methane concentration in soil gas prior to the start of vapor extraction was unexplainably high. For many vadose zone monitoring wells, the instrument reading of methane was greater than 100 percent prior to the start of vapor extraction.

Of course, a methane concentration greater than 100 percent is not possible, and, given the circumstances of this air injection process, it is unlikely that the concentration could be more than a few percent methane. The instrument uses infrared detection to quantify methane. This method will also detect the presence of other low molecular weight alkanes and the instrument's response to interfering compounds is apparently much greater than the response to methane. The net result is an instrument reading of methane that is much higher than the combined concentration of methane and the other volatile organic compounds present. Thus the actual concentration of methane and other organic vapors in the soil gas can not be quantified, based on the instrument reading. It should also be noted that the instrument used to obtain methane concentration was calibrated daily with a 15 percent methane standard and it consistently read within one percent of the standard concentration prior to daily calibration.

The instrument is relatively accurate in reading pure methane. The problem with instrument readings occurs when interfering compounds are present that provide a much higher instrument response than methane.

The combined instrument reading of methane and other interfering compounds is referred to, in this report, as the instrument reading of methane. It should be understood that this reading includes more than simply methane and that the actual concentration of volatile organics measured by this technique can not be quantified.

The rate of volatiles production was estimated based on data obtained from the period of time when the sparge system operated without vapor extraction. When the extraction blower was shut off, soil gas generated by air sparging was allowed to accumulate in the vadose zone. This allowed the "loading" of the vadose zone with vapors generated by the air sparging in much the same manner as would occur at this site in the absence vapor extraction. Sparging was continued for 11 hours after the vacuum extraction system was shut off.

Table 4-5 lists the soil gas constituents at the end of the 11 hour period of sparging without vapor extraction. Of the gas constituents presented in Table 4-5, helium provides the best indication of whether the gas has been derived entirely from sparging. Helium was injected at a concentration of two percent during the 11 hour period. Following this, wells MP1A, MP1B, MP1C, MP3A, MP3B, MP3C, MP4B, MP4C, and MP6 all have helium concentrations at or near two percent. The helium concentration of two percent is an indication that the soil gas present was derived from sparge air.

The wells with near two percent helium concentration also had oxygen concentrations near atmospheric (19.5 - 19.9 percent), and carbon dioxide concentrations of less than 0.5 percent. The only significant difference between the soil gas measured at these wells and the air injected into the sparge well is the presence of volatile organic compounds. The methane concentration

TABLE 4-5

SOIL GAS RESULTS AFTER 11 HOURS OF SPARGE-ONLY
SITE SS-06
WURTSMITH AFB, MICHIGAN

Well	CH4* %	He %	O2 %	CO2 %	VOCs (ppmv)
MP1A	55.3	2.0	19.5	0.0	435
MP1B	45.1	2.0	19.7	0.0	444
MP1C	29.7	1.9	19.5	0.0	439
MP2A	21.4	0.08	17.2	1.9	391
MP2B	39.4	0.33	16.2	3.0	318
MP2C	150	1.1	17.8	3.3	170
MP3A	26.6	1.9	19.8	0.1	449
MP3B	25.9	2.0	19.9	0.0	453
MP3C	21.6	2.1	19.7	0.0	486
MP4A	54.4	1.5	19.3	0.8	330
MP4B	90.6	1.9	19.5	0.5	278
MP4C	88.9	2.0	19.5	0.5	289
MP5A	90.1	0.85	17.4	2.3	246
MP5B	92.7	1.1	17.8	3.2	200
MP5C	150	1.6	18.8	1.6	129
MP6	47.5	2.0	19.6	0.0	426

*Methane concentrations are reported as instrument readout. Actual concentration can not be quantified.

of this soil gas was recorded as between 29.7 and 88.9 percent (Table 4-5). As discussed earlier, this reading is not usable.

The following method was used to estimate the highest possible concentration of methane and other volatile compounds at the end of the sparge-only period (without use of the instrument methane readings). The oxygen content of the air taken into the blower for sparging was assumed to be approximately 21 percent. The concentration of other gases in the air was therefore 79 percent (nitrogen, argon, carbon dioxide, etc.). Prior to injection, helium is added to provide a final concentration of 2 percent and sulfur hexafluoride is added to provide a final concentration of 0.3 percent. The final concentration of oxygen in the sparge air (following injection of helium and sulfur hexafluoride) was then about 20.5 percent and the concentration of other gases was 79.5 percent.

The air that accumulated in the vadose zone following sparging (at wells where nearly 2 percent helium was detected) contained an average of 19.6 percent oxygen. If it is assumed that the air just passed through the water and stripped volatile components (such as methane) and carbon dioxide without transferring oxygen to groundwater, the concentration of gases other than oxygen from the original sparge air would be 75.5 percent (using the same proportion to the original concentration as the oxygen). This leaves a maximum potential concentration of new gases of 4.9 percent. The new gases would include methane, other volatiles, and carbon dioxide. The average concentration of carbon dioxide (in the same set of wells) was 0.125 percent, and it is assumed that this concentration is entirely the result of stripping from groundwater. Therefore the maximum possible concentration of stripped volatile organic compounds was about 4.8 percent.

Some oxygen transfer may have occurred as the air traveled through the aquifer to the vadose zone. The amount of this transfer is expected to be small due to the fact that the groundwater in contact with the sparge channels would already have near saturation levels of oxygen due to the long period of prior sparging. Some oxygen could also have been consumed in the vadose

zone due to biological or chemical oxygen demand. Section 4.4 discusses the biological degradation rate of oxygen in the vadose zone. Based on findings presented in Section 4.4, it is unlikely that this would account for the observed short term decline in oxygen in the sparge air.

Based on the high instrument reading for methane and the 4.8 percent of soil gas unaccounted for in the above analysis, it was assumed that methane and other organic compounds totaled 4.8 percent in the soil gas following the sparge-only period. This 4.8 percent would include the compounds identified by PID readings and in the laboratory analysis of the soil gas at the end of the sparge-only period. This provides a measure of the maximum possible stripping efficiency of the sparge air.

The soil gas samples also contained an average, by instrument reading, of 42.6 percent methane. As discussed above, the instrument reading at best provides a qualitative measure of the presence of methane and other volatile organic compounds. For the purpose of this discussion, it is assumed that the soil gas contained 4.8 percent volatile organic compounds based on the discussion in Section 4.3.6.

Given that the sparge air was injected at approximately 22 scfm, assumed volatile organic compound concentration of the resulting soil gas is 4.8 percent, the rate of volatiles production by a single sparge well operated under these conditions was 1.06 scfm.

4.4.2 Oxygen Consumption Rate

An oxygen consumption rate was estimated based on the assumption that the volatile load was composed largely of methane. Simple aerobic degradation of the methane proceeds by the stoichiometry of Equation 11.

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \qquad \text{Equation 11}$$

One mole of methane requires 2 moles of oxygen for complete degradation to carbon dioxide and water. Assuming ideal gases for oxygen and methane and the methane production rate of 1.06 scfm calculated above, it would require 2.12 scfm of oxygen to degrade the methane and other volatiles generated by sparging. The sparge air within the vadose zone will contain approximately 19.6 percent oxygen. Therefore, approximately 10.8 scfm of sparge air would be required to degrade the volatile load assumed generated in the sparge-only test. Based on this calculation, the sparge air would provide sufficient oxygen for biological degradation.

4.4.3 Biological Degradation Rate

After the sparge-only test was terminated, the soil gas constituents were as shown in Table 4-5. This soil gas had a near atmospheric concentration of oxygen, only a small concentration of carbon dioxide, a helium concentration near 2 percent, and as estimated above an average methane (and other organic compounds) concentration of less than 4.8 percent. This represented the starting point for the *in situ* respiration test.

Soil gas measurements were continued for a total of 19 days. The measurements were initially taken at a daily interval and were spaced further apart toward the end of the measurement period. Figure 4-4 shows the rate of decline in oxygen and helium in well MP3C. The plot shows oxygen declining steadily over the course of the monitoring period. Helium is also seen to decline to zero in a shorter period of time. Other monitoring wells at the C level showed similar rates of decline. A listing of the soil gas data, and plots of the soil gas constituents for all of the vadose zone monitoring wells, is provided in Appendix B.

The rate of oxygen concentration decline was progressively less in the B level wells and the A level wells. However, oxygen decline was observed in all vapor monitoring wells. Table 4-6

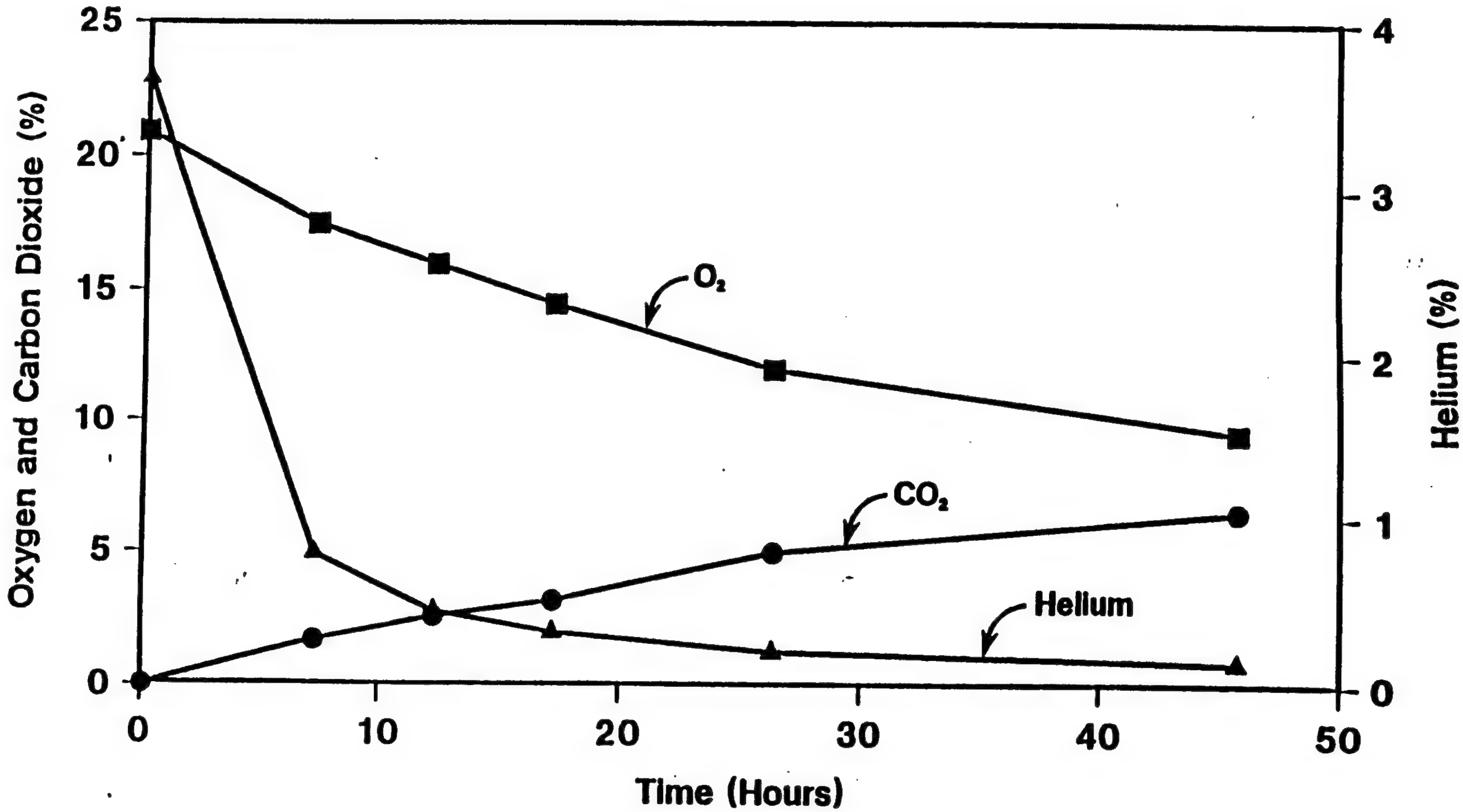
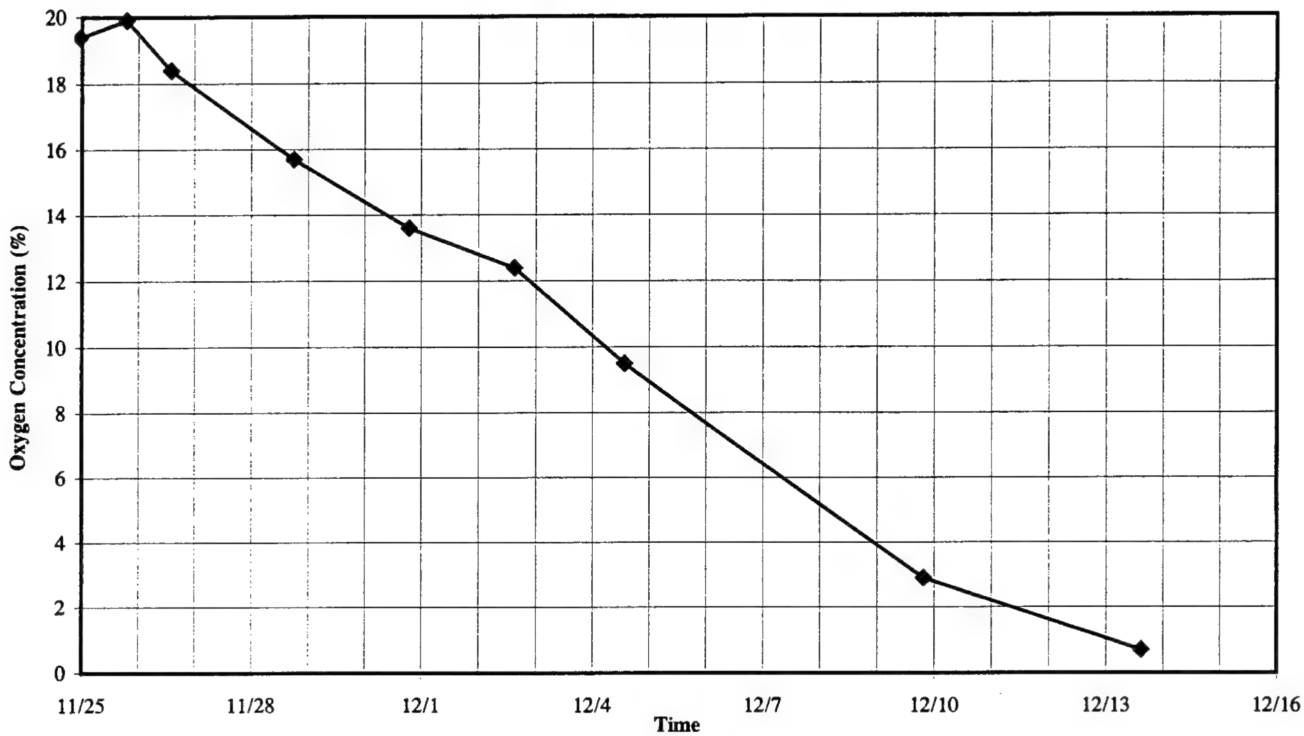


Figure 5-4. In Situ Respiration Test Results for Monitoring Point K3, Kenai, Alaska.

FIGURE 4-4
OXYGEN AND HELIUM CONCENTRATION OF WELL MP3C
SITE SS06
WURTSMITH AFB, MICHIGAN

Oxygen Concentration (%)



Helium Concentration (%)

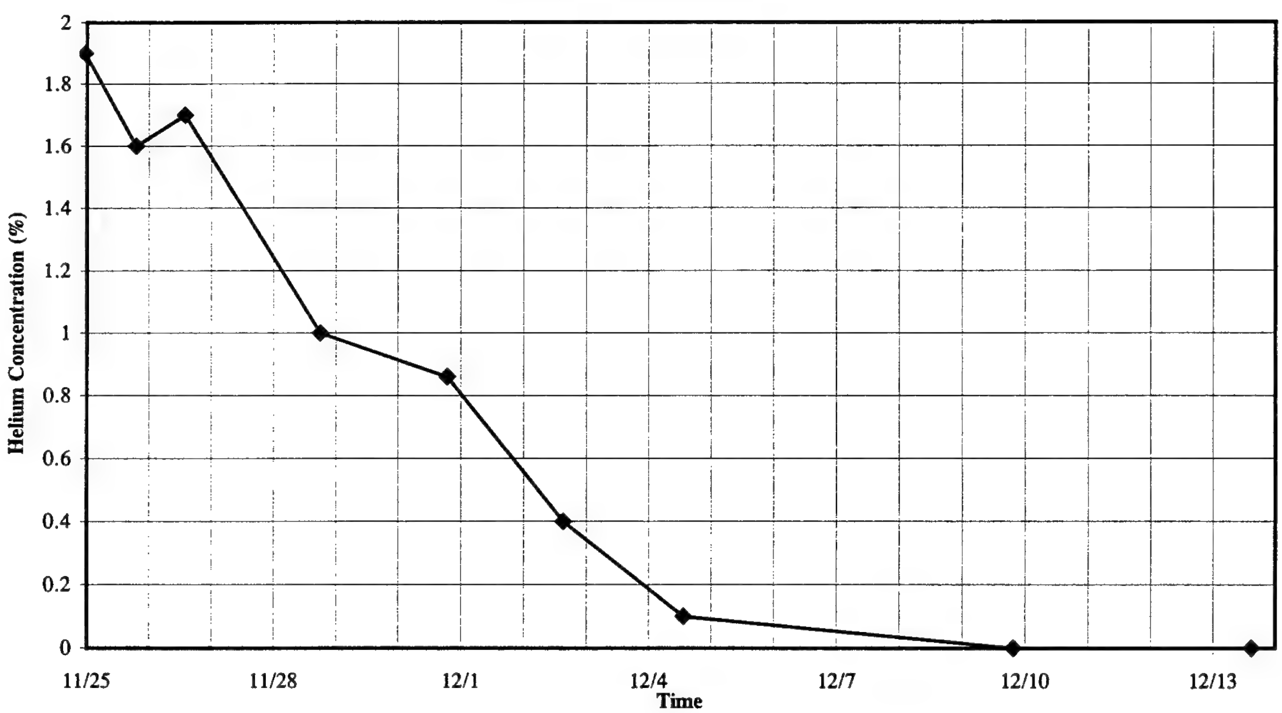


TABLE 4-6
OXYGEN DEPLETION RATES IN VADOSE ZONE MONITORING WELLS
SITE SS-06
WURTSMITH AFB, MICHIGAN

Well	Oxygen Initial Reading (%)	Oxygen Final Reading (%)	Oxygen Change (%)	Time Interval (hours)	Oxygen Decline Rate (%O2/hr)
MP1A	20.6	16.9	3.7	409.55	0.009
MP1B	17.2	6.0	11.2	209.98	0.053
MP1C	19.1	6.9	12.2	209.98	0.058
MP2A	19.9	17.0	2.9	470.57	0.006
MP2B	17.4	11.2	6.2	470.57	0.013
MP2C	18.1	5.7	12.4	139.25	0.089
MP3A	20.8	16.3	4.5	235.63	0.019
MP3B	19.5	10.0	9.5	235.63	0.040
MP3C	19.9	2.9	17	336.55	0.051
MP4A	19.8	18.2	1.6	470.13	0.003
MP4B	19.5	12.6	6.9	470.13	0.015
MP4C	19.5	2.9	16.6	234.57	0.071
MP5A	20.2	16.8	3.4	474.15	0.007
MP5A	17.8	10.5	7.3	474.15	0.015
MP5B	18.8	5.3	13.5	144.20	0.094
MP6	19.6	11.2	8.4	358.75	0.023

lists the data and results for the oxygen depletion calculations for each monitoring well. The average rate of oxygen decline for the wells was 0.035 percent oxygen per hour.

The helium decline data presented in Figure 4-4 indicates that diffusion could be a factor in the oxygen changes observed during the test. However, helium diffuses at approximately 3 times the rate of oxygen (given the same gradient) and the gradient for helium would be large and directed away from the test site in all directions. For oxygen, the gradient would not be as large, and would be directed into the test area from the ground surface and away from the test area at the horizontal fringe of the injected air mass in the vadose zone. For this analysis, the effect of oxygen diffusion away from the test area was assumed negligible and the observed oxygen decline was assumed to be only the result of biological degradation. The following calculation will represent the maximum possible biological degradation rate. Assuming a design sparge well spacing of 60 feet, the surface area attributable to a single sparge well would be 3600 square feet. The vadose zone depth is 22 feet at this site, resulting in a total soil volume of 79,200 cubic feet. This is the soil volume that could contribute to biodegradation of volatile organic compounds. The air filled porosity was assumed to be 20 percent of this volume, based on the results of the transient air permeability tests. This results in a soil gas volume of 15,840 cubic feet of which 3,105 cubic feet would be oxygen (19.6 percent).

The average reduction in percent oxygen composition of the soil gas was 8.6 percent (average of values presented in Table 4-6). Applying this to the soil gas volume of 15,840 cubic feet, 1362 cubic feet of oxygen was consumed in an average time of 334 hours. This results in an oxygen consumption rate of 4.08 cubic feet per hour or 0.068 scfm. It takes two moles of oxygen to degrade one mole of methane and thus the maximum biological degradation rate for methane would be 0.034 scfm.

Comparing the maximum methane degradation rate to the previously estimated volatiles production rate (1.06 scfm) it can be seen that the biological degradation rate is significantly

lower than the assumed volatiles production rate. The volatiles production rate is higher than the biological degradation rate by a factor of about 30.

Many assumptions were used in the calculation of the volatiles production rate and the calculation of biological degradation rate, resulting a in large degree of uncertainty in the overall analysis. However, the analyses presented indicate a likelihood that biological degradation will not be able to keep pace with volatiles production. In order to make the decision to conduct air sparging without vapor extraction it would be necessary to provide strong arguments with the opposite conclusion to that provided above.

Additional considerations include the potential for the accumulation of explosive gases beneath structures in the remediation area. The instrument used to measure methane is also used as a instrument to measure the lower explosive limit (LEL). When used in the LEL mode, the instrument indicated greater than 100 percent LEL in some monitoring probes. The same interferences are present for the LEL measurement and thus this reading is also suspect. However, it would not be prudent to allow the accumulation of gases that may approach the LEL beneath structures in this area.

4.5 SOIL VAPOR CHEMICAL RESULTS

Soil gas volatiles data were collected from the monitoring wells and from the extracted vapor stream. These data were generally taken using field instruments, but two soil gas samples were collected in summa canisters and sent for laboratory for analysis. The soil gas sampling for field and laboratory analysis have been discussed above with respect to other tests. In this section, the results are evaluated to provide an estimate of the volatile loading that can be expected in the soil vapor stream for full scale implementation.

PID readings of the extracted soil gas ranged from 214 ppmv to 971 ppmv, with an overall average of 417 ppmv. Methane and other light volatile compounds were likely present in the extracted soil gas but the concentration could not be quantified.

The first laboratory analytical sample was obtained from the discharge air of the SVE system prior to the start of AS. A summary table of the results of this sampling is included in Appendix B. The complete laboratory data set with QA/QC sheets is provided in Appendix E. The total VOC concentration for this analysis (averaged between the sample and the duplicate) was 216 ppmv.

4.6 VACUUM WELL SPACING FOR FULL SCALE SYSTEM

The appropriate spacing for the vacuum extraction wells was determined as follows. The air flow rate for a single extraction well, determined in Section 4.2 was 300 scfm. This rate allowed a near maximum flow rate from a single well without the steep increase in required vacuum observed at the next flow level tested (350 scfm). The air permeability soil characteristics discussed in Section 4.1, using the numerical model, were 50 darcies for horizontal permeability and 17.7 darcies for vertical permeability and the permeability of the surface soil. The desired sparging rate was 25 scfm for each well with sparge wells spaced 60 feet on center.

A numerical model was constructed with the above soil permeability characteristics. Nine extraction wells were incorporated into the model, and only the capture zone of the center well was evaluated. The wells surrounding the center well were used to provide the effects of adjacent recovery wells to the model. The influence of the sparge wells was included in the model as injection wells in the lowest model layer in each model grid cell. The overall injection rate by the sparge wells corresponded to the rate obtained by wells spaced 60 feet on center and injecting a net 11 scfm of sparge air, but this was placed into the model cell by cell based on the proportional area of a given model cell. The effects of water table mounding

were also incorporated into the model by reducing the permeability of the lowest layer based on the proportion of the layer which would be flooded with rising water table (i.e. if the water table at the location of a given cell was expected to rise one foot and the layer thickness was two feet, the permeability of the cell was reduced by a factor of two).

The distance between the wells was adjusted to provide adequate capture of the sparge vapors. An extraction well spacing of 150 feet on center allowed for complete capture of sparge air. This spacing was reduced to provide a safety factor and to provide an easier design distance of 120 feet (twice the sparge well spacing).

The numerical model can be used to further optimize the design for full scale installation. In some areas it would be appropriate to extend the distance between extraction wells up to 150 feet and greater distances will also be possible in areas with low permeability surface cover. In some areas it may also be possible to reduce the flow rate of individual wells and thereby reduce the required flow rate for the system. However, a maximum spacing of 120 feet can be used for design purposes without further modeling.

5.0 RESULTS AND DISCUSSION FOR SITE SS-08 LOCATION A

The air permeability testing was conducted between November 25, 1997, and December 1, 1997. The results of these tests are presented and discussed in the following subsections. Air sparging pilot tests were not conducted at Site SS-08 Location A. Air sparging tests for Site SS08 were conducted at Site SS-08 Location B.

5.1 AIR PERMEABILITY

Short term transient and short term steady state air permeability tests were conducted at Site SS-08 Location A. Details of the pilot testing system and the extraction and observation wells are provided in Section 2 and details of the methods used to conduct and analyze the tests are included in Section 3.

Steady state data were collected from each of the monitoring wells at several times following the start of vacuum extraction. Table 5-1 provides the vacuum data from the steady state test. It was determined that steady state was reached very early in the test. Only minor increases in vacuum occurred in any of the wells after the first reading at 10 minutes into the test. Any of the data collection times listed in Table 5-1 were acceptable for the calculation of steady state permeability. The data from November 25, 1997 were used in the steady state calculations discussed below.

Three analytical methods were used to calculate air permeability from the steady state data: the effective radius method, the two well steady state method, and the two well pseudo steady state method. Tables summarizing the data input to determine air permeability and the resulting calculated values of permeability are included in Appendix C for each method. Example calculation for each method are also included in Appendix C.

TABLE 5-1
STEADY STATE VACUUM TEST RESULTS
SITE SS-08 LOCATION A
WURTSMITH AFB, MICHIGAN

	11/25/97 19:30	11/25/97 21:02	11/25/97 23:07
MP6	18.88*	19.24	19.20
MPIA	7.89	7.92	7.84
MP1B	8.18	8.46	8.39
MP2A	5.74	5.98	5.93
MP2B	5.87	6.14	6.08
MP3A	3.60	3.76	3.70
MP3B	4.06	4.21	4.14
MP4A	1.61	1.69	1.63
MP4B	1.91	1.96	1.93
MP5A	1.20	1.24	1.26
MP5B	1.38	1.42	1.43

Flow Rate = 152 scfm
Test started 11/25/97, 19:20
* all values in inches of water column vacuum

The effective radius method required an estimation of the effective radius of vacuum influence for the test. As discussed in Section 3, this was estimated using a distance-drawdown plot. The effective radius determined from the plot was 54 feet. The distance drawdown plot used to estimate the effective radius is included in Appendix C.

Analysis of the transient test data involved type curve matches between the transient data (plotted as log-log) and the Hantush-Jacob leaky confined type curves. The log-log data plots for each test are included in Appendix C, and the type curves used for matching are shown on Figure 3-2. A summary of the match points chosen for each test and example calculations are included in Appendix C.

Table 5-2 provides a summary of the air permeability results from the steady state and transient methods used to analyze the test data. Calculated permeability values varied from a low of 8.6 darcys to a high of 110.6 darcys with an overall average of 43.5 darcys. This represents greater than an order of magnitude variation within the wells and methods tested. No clear trend in permeability calculations is present in this summary data. The calculated permeability values for the two well method and the pseudo steady state method may show in increasing trend in calculated permeability with distance from the extraction well, but this trend is not seen with all of the analytical methods used. The lack of this type of trend (in comparison to the other two sites tested) may be the result of less vertical leakage at this site due to the surface cover of tarmack, and it may be an indication that analytical methods will provide reliable estimates of permeability at this site. However, the spread of calculated permeability values between analytical methods still allow considerable variation in estimates of required radius for a full scale SVE system.

A numerical model was used as a last step in estimating the soil permeability characteristics at this site. The results of the transient leaky analytical model were used as a starting point for the numerical model. The numerical finite difference model MODFLOW was used for this analysis as described in Section 3. Model runs were completed and compared to the steady

TABLE 5-2
SUMMARY OF SOIL PERMEABILITY RESULTS
SITE SS-08 LOCATION A
WURTSMITH AFB, MICHIGAN

	Effective Radius Method (darcys)	2 Well Steady State Method (darcys)	Pseudo Steady State Method (darcys)	Transient Method (darcys)	Average (darcys)
MP1	62.8	55.3	9.6	27.1	38.7
MP2	57.8	54.0	8.8	20.0	35.2
MP3	65.3	49.0	8.6	17.7	35.2
MP4	91.3	94.4	15.0	37.3	59.5
MP5	42.2	110.6	17.9	---	56.9
Average	63.9	72.7	12.0	25.5	43.5

state data for each vadose zone monitoring well (at each level). The model allowed a better use of the available data and allowed incorporation of three dimensional flow to the vapor extraction well.

The model was run and permeability values for the vadose zone and the surface soil were adjusted until a best fit with the field data was obtained. The best fit was attained using a horizontal and vertical air permeability of 50.6 darcies, and a surface layer permeability of 1.8 darcies (one foot thick surface layer). The horizontal air permeability value determined for the model was within the range of values determined using the analytical methods and was relatively close to the overall average of the values obtained by the various analytical methods (44.8 darcies).

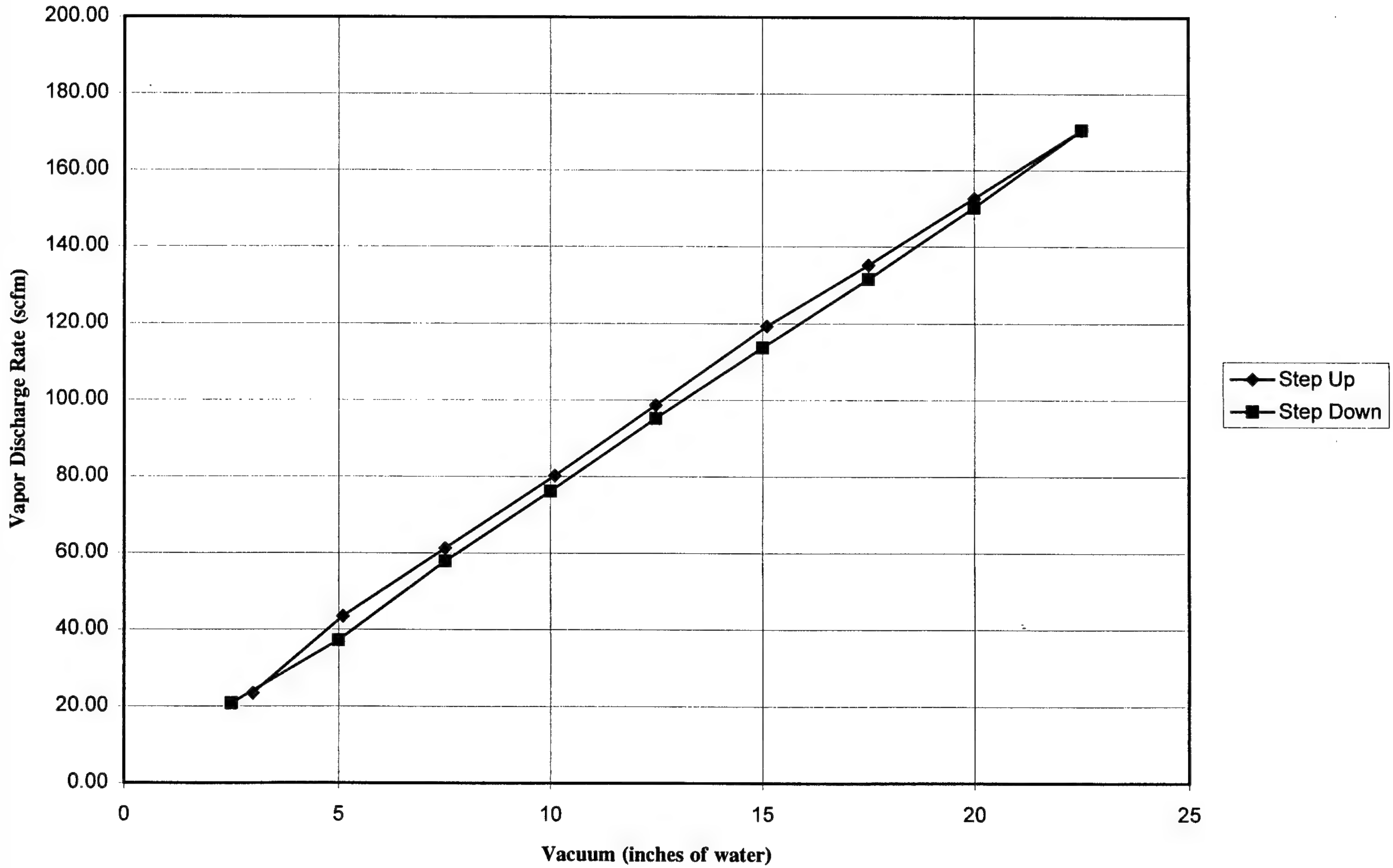
5.2 VACUUM/FLOW RATE CORRELATION

A vacuum step test was conducted for Site SS-08 Location A on November 25, 1997 using the methods described in Section 3. The test was conducted with increasing vacuum up to the maximum available rate/ vacuum. The test was then stepped back down to zero vacuum. The results of the test are plotted on Figure 5-1. The legend on Figure 5-1 indicates whether the data are from the step up or step down portion of the test. Tabular data from the step test are included in Appendix C.

The step test data show a nearly linear trend of vacuum versus air flow rate. The specific yield for the well calculated from this test is approximately 7.55 scfm per inch water column of applied vacuum. Stated in terms of vadose zone thickness this yield is approximately 0.63 scfm per inch water column vacuum per foot of unsaturated formation.

A numerical model was used to extend the vacuum versus flow rate relation curve to higher vacuums than were possible with the pilot test equipment. The extended curve indicated a

FIGURE 5-1
VACUUM STEP TEST
SITE SS-08 LOCATION A
WURTSMITH AFB, MICHIGAN



large in the required vacuum when the flow rate was increased to 300 scfm from 250 scfm. The design flow rate per vacuum well was chosen at 250 scfm, based on these results.

5.3 BACKGROUND SOIL GAS CONSTITUENTS

The background soil gas concentration of field measured parameters was conducted at Site SS-08 Location A prior to the start of air permeability testing. The results of the soil gas analyses is provided in Table 5-3. The background conditions indicate some depression in oxygen concentration and an elevation in carbon dioxide levels (in comparison to uncontaminated soils).

5.4 VACUUM WELL SPACING FOR FULL SCALE SYSTEM

The appropriate spacing for the vacuum extraction wells was determined as follows. The air flow rate for a single extraction well, determined in Section 5.2 was 250 scfm. This rate allowed a near maximum flow rate from a single well without the steep increase in required vacuum observed at the next flow level tested (300 scfm). The air permeability soil characteristics discussed in Section 5.1, using the numerical model, were 50.6 darcies for horizontal and vertical permeability and 1.8 darcies for vertical and horizontal permeability of the surface soil. The desired net sparging rate was 11 scfm for each well with sparge wells spaced 50 feet on center (see Section 6.3.7, below).

A numerical model was constructed with the above soil permeability characteristics. The model set-up was as described for site SS-06 except the characteristics determined for site SS-08 Location A were incorporated.

TABLE 5-3
BACKGROUND SOIL GAS READINGS FROM NOVEMBER 25, 1997
SITE SS-08 LOCATION A
WURTSMITH AFB, MICHIGAN

Well	%02	%CO2	%CH4	PID (ppm)
MP6	9.8	10.5	0	14.6
MP1A	9.7	10.4	0	7.9
MP1B	9.5	10.6	0	6.6
MP2A	6.2	12.1	0	7.9
MP2B	6.1	12.2	0	9.3
MP3A	10.1	10.1	0	5.3
MP3B	9.8	10.3	0	14.6
MP4A	16.7	4.5	0	3.9
MP4B	15.3	5.5	0	5.3
MP5A	11.8	7.7	0	6.6
MP5B	11.6	8	0	3.9

The distance between the wells was adjusted to provide adequate capture of the sparge vapors. An extraction well spacing of 140 feet on center allowed for complete capture of sparge air. This spacing was reduced to provide a safety factor and to provide an easier design distance of 100 feet (twice the sparge well spacing).

The numerical model can be used to further optimize the design for full scale installation as discussed above for site SS-06. However, a maximum extraction well spacing of 100 feet can be used in site SS-08 without the need for further modeling.

6.0 RESULTS AND DISCUSSION FOR SITE SS-08 LOCATION B

The air permeability testing, the long term vapor extraction pilot test, and the air sparging pilot test were conducted between December 2, 1997, and December 14, 1997. The results of these tests are presented and discussed in the following subsections. A summary table of the SVE pilot system and AS pilot system operational data for Site SS-08 Location B testing is provided in Appendix D.

6.1 AIR PERMEABILITY

Short term transient and short term steady state air permeability tests were conducted at Site SS-08 Location B. Details of the pilot testing system and the extraction and observation wells are provided in Section 2, and details of the methods used to conduct and analyze the tests are included in Section 3.

Steady state data were collected from each of the monitoring wells at several times following the start of vacuum extraction. Table 6-1 provides the vacuum data from the steady state test. It was determined that steady state was reached very early in the test. Significant increasing trends in vacuum did not occur in any of the wells after the first reading taken at 10 minutes into the test. Thus, any of the data collection times listed in Table 6-1 were acceptable for the calculation of steady state permeability. The data from November 3 at 8:22 AM were used in the steady state calculations.

Three analytical methods were used to calculate air permeability from the steady state data: the effective radius method, the two well steady state method, and the two well pseudo steady state method. Summary tables of data used to determine air permeability, example calculations, and the calculated values of permeability for each method are included in Appendix D.

TABLE 6-1
STEADY STATE VACUUM TEST RESULTS
SITE SS-08 LOCATION B
WURTSMITH AFB, MICHIGAN

	12/2/97 21:45	12/2/97 22:15	12/3/97 8:22	12/3/97 14:10	12/3/97 19:10	12/4/97 11:35	12/5/97 8:35
MP1A	3.62*	3.61	3.53	3.50	3.60	3.52	3.22
MP1B	5.19	5.06	4.89	4.88	4.95	4.81	3.61
MP2A	2.23	2.19	2.14	2.18	2.30	2.17	1.91
MP2B	2.72	2.63	2.55	2.59	2.54	2.50	2.23
MP3A	1.64	1.54	1.51	1.55	1.64	1.51	1.30
MP3B	1.82	1.71	1.67	1.70	1.81	1.69	1.49
MP4A	0.46	0.37	0.33	0.36	0.40	0.39	0.30
MP4B	0.55	0.46	0.41	0.45	0.50	0.46	0.37
MP5A	0.16	0.15	0.11	0.17	0.18	0.16	0.13
MP5B	0.21	0.20	0.16	0.20	0.23	0.19	0.18
MP6	13.50	13.78	13.80	13.99	14.14	14.10	14.02
Port 1	15.54	15.90	15.78	16.15	16.30	-	16.22

Test start time = 12/2/97, 21:35
Flow rate = 176 scfm
* values in inches of water column vacuum

The effective radius method also required an estimation of the effective radius of vacuum influence for the test. As discussed in Section 3, this was estimated using a distance-drawdown plot. The effective radius determined from the plot was 44 feet. The distance drawdown plot used to estimate the effective radius is shown on Figure 3-1. A summary of the input parameters used for these equations, example calculations, and results of the analyses are also included in Appendix D.

Analysis of the transient test data involved type curve matches between the transient data (plotted as log-log) and the Hantush-Jacob leaky confined type curves. The log-log data plots for each test are included in Appendix D, and the type curves used for matching are shown on Figure 3-2. A summary of the match points chosen for each test and example calculations are included in Appendix D.

Table 6-2 presents an overall summary of the air permeability results from the steady state and transient methods used to analyze the test data. Calculated permeability values vary from a low of 15.6 darcys to a high of 258.8 darcys with an overall average of 89.4 darcys. This represents greater than an order of magnitude variation within the wells and methods tested. The general trend in the data summarized in Table 6-2 is toward increasing permeability estimates with increasing distance from the extraction well.

As discussed in Section 4.1, this trend does not represent a real trend in permeability with distance from the well but is an indication of the limitations of analytical methods when treating air flow under conditions of leakage from the surface. For this data set, the transient analyses do not show a trend of increasing permeability estimates with distance. Of the methods used, the transient method is the only one that had the capability of evaluating leakance from the soil surface. However, the transient method still treats the flow system as one dimensional and radial. The problems associated with the using the assumption of one dimensional flow were discussed in Section 4.1 with respect to Site SS-06.

TABLE 6-2
SUMMARY OF SOIL PERMEABILITY CALCULATIONS
SITE SS08 LOCATION B
WURTSMITH AFB, MICHIGAN

	Effective Radius Method (darcys)	Steady State Two Well Method (darcys)	Pseudo Steady State Method (darcys)	Transient Type Curve Method (darcys)	Average (darcys)
MP1	113.8	91.5	15.6	34.5	63.9
MP2	139.8	122.4	19.9	11.3	73.3
MP3	136.0	112.4	18.9	18.4	71.4
MP4	258.8	155.9	24.6	13.6	113.2
MP5	174.2	172.9	27.9	-	125.0
Average	164.5	131.0	21.4	19.4	89.4

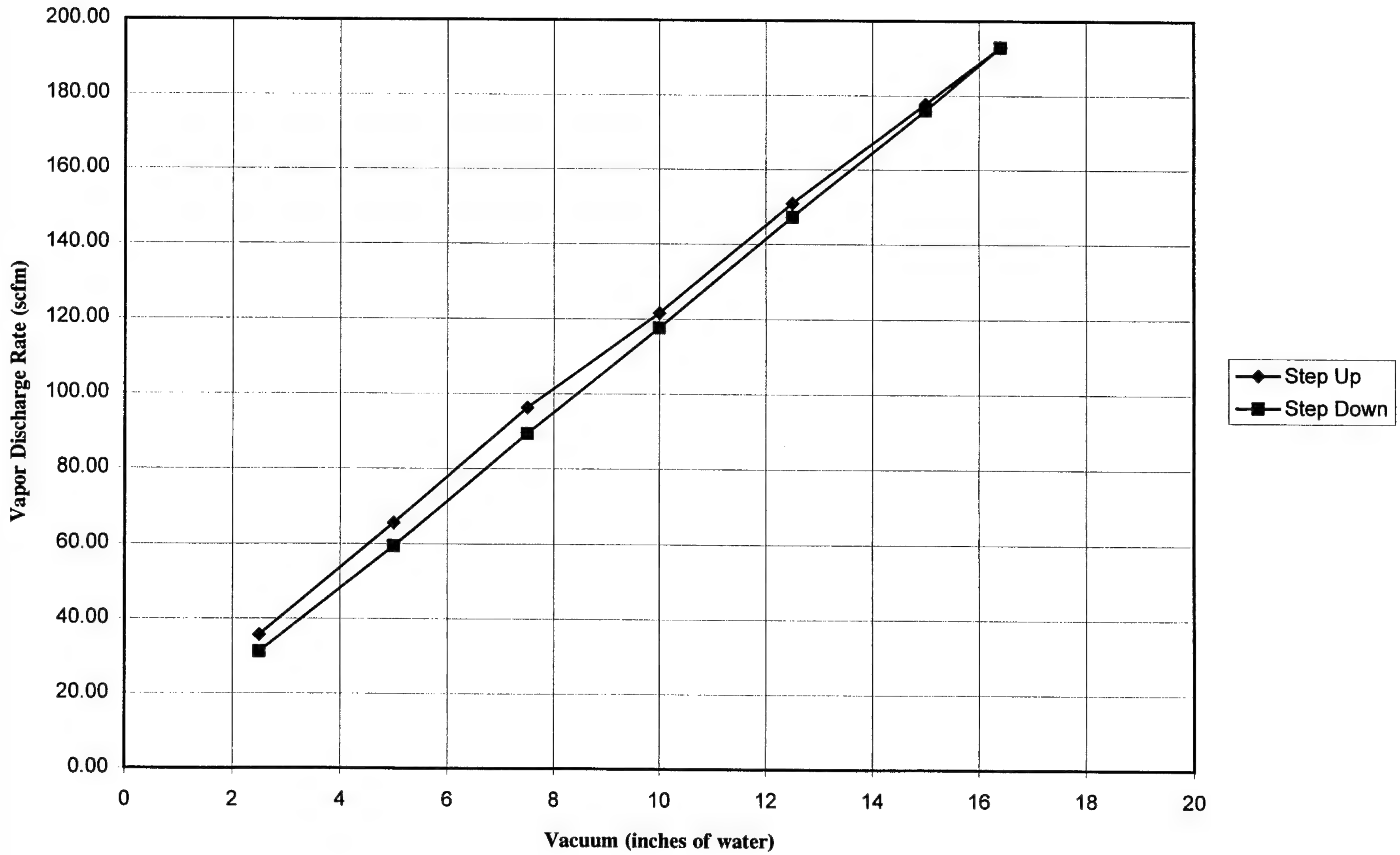
A numerical model was used as a last step in estimating the soil permeability characteristics at this site. The results of the transient leaky analytical model were used as a starting point for the numerical model. The numerical finite difference model MODFLOW was used for this analysis as described in Section 3. Model runs were completed and compared the steady state data for each vadose zone monitoring well (at each level). The model allowed a better use of the available data and allowed incorporation of three dimensional flow to the vapor extraction well.

Model runs were completed and permeability values for the vadose zone and the surface soil were adjusted until a best fit with the field data was obtained. The fit provided by the model was considerably better at all locations than the fit provided by any of the analytical methods. The best fit was attained using a horizontal air permeability of 55 darcies, a vertical air permeability of 25 darcies and a surface layer vertical and horizontal air permeability of 20 darcies. Areas of the site that were covered by less permeable materials such as the road and the parking lot were given a lower surface layer permeability in the model. The horizontal air permeability value determined for the model was within the range of values determined using the analytical methods, but was somewhat lower than the overall average of the values obtained by the various analytical methods (89.4 darcies). The higher permeability values obtained by the analytical methods were probably the result of significant surface leakage at this site that makes the permeability "appear" higher to methods that do not account for the leakage and for non-horizontal flow.

6.2 VACUUM/FLOW RATE CORRELATION

A vacuum step test was conducted for Site SS-08 Location B using the methods described in Section 3. The test was conducted by increasing vacuum in steps up to the maximum available rate/ vacuum. The test was then stepped back down to zero vacuum. The results of the test are plotted on Figure 6-1. The legend on Figure 6-1 indicates whether the data are from the

FIGURE 6-1
VACUUM STEP TEST
SITE SS-08 LOCATION B
WURTSMITH AFB, MICHIGAN



step-up or step-down portion of the test. Tabular data from the step test is included in Appendix D.

The step test data show a nearly linear trend of vacuum versus air flow rate. The specific yield for the well calculated from this test is approximately 11.7 scfm per inch of water column of applied vacuum. Stated in terms of vadose zone thickness, this yield is approximately 0.78 scfm per inch of water column vacuum per foot of unsaturated formation.

A numerical model was used to extend the vacuum versus flow rate relation curve to higher vacuums than were possible with the pilot test equipment. The extended curve indicated a significant increase in the required vacuum when the flow rate was increased from 350 scfm to 400 scfm. The design flow rate per vacuum well was chosen at 300 scfm, based on these results. This design flow rate is acceptable for all areas of Site SS-08 Location B designated for AS/SVE where surface cover is not present. A lower flow rate of 250 scfm should be applied where the surface is covered with pavement or structures (Section 5.2).

6.3 AIR SPARGING TEST

Air sparging tests were conducted at Site SS-08 Location B using the air sparging pilot test equipment discussed in Section 2 and according to the methods described in Section 3. The results of the sparging tests and a discussion of those results are provided below. The most important determinations for this test was the radius of influence for the sparge well and the depth of sparging influence in the aquifer. Other factors considered were the effects of sparging on volatiles in the vadose zone, the effects of pulsing the sparge system, and the effects of sparging on other water chemistry parameters. These effects were established in the test by observing changes in the concentration of dissolved oxygen, changes in ORP, the presence of helium at specific locations in the vadose zone, the presence of sulfur hexafluoride in groundwater, and changes in these parameters occurring after the end of the sparging. The test results are discussed in terms of these indicator parameters in the following subsections.

6.3.1 Dissolved Oxygen Results

Dissolved oxygen is a primary indicator parameter for the performance of an air sparging system. As sparge air is released into the aquifer it travels through the saturated zone in air phase channels. These channels are in contact with water coated aquifer material and groundwater at the margins of the channels. The contact between air and groundwater allows exchange of oxygen to the aquifer and volatile organic constituents to the air stream. As a result, areas of the aquifer which are effected by sparging typically show an increase in dissolved oxygen content.

Dissolved oxygen concentration of groundwater at each of the groundwater monitoring wells was determined approximately daily through a period extending from 6 days before the start of the sparging test until 3 days after the sparging had ended. An *in situ* respiration test was not conducted at this site due to the lack of volatiles found in background vapor sampling and throughout the AS and SVE pilot tests. The dissolved oxygen content of groundwater was plotted over this time period for each monitoring well to aid in determining if the well had been effected by the sparging. Figure 6-2 is a plot of dissolved oxygen for well MP3C. The initial level of dissolved oxygen at this well was less than 1 mg/L.

As shown in Figure 6-2, the dissolved oxygen concentration in the well increased gradually after the start of sparging to 1.17 mg/L after one day. The dissolved oxygen concentration declined slightly during the second day to 1.13 mg/L, but then increased steadily to greater than 5 mg/L by the end of the test. Air sparging ended on December 11, and the dissolved oxygen level declined on December 11 and on each day of follow-up sampling.

Plots of dissolved oxygen levels at each of the other monitoring wells are included in Appendix D. Table 6-3 summarizes the results of these plots. All groundwater monitoring wells showed an increase in dissolved oxygen during and/or following the air sparging. The general trend was similar to the trend exhibited in Figure 6-2, although two wells (MP1D and MP1E)

FIGURE 6-2
DISSOLVED OXYGEN CONCENTRATION FOR WELL MP3C
SITE SS-08 LOCATION B
WURTSMITH AFB, MICHIGAN

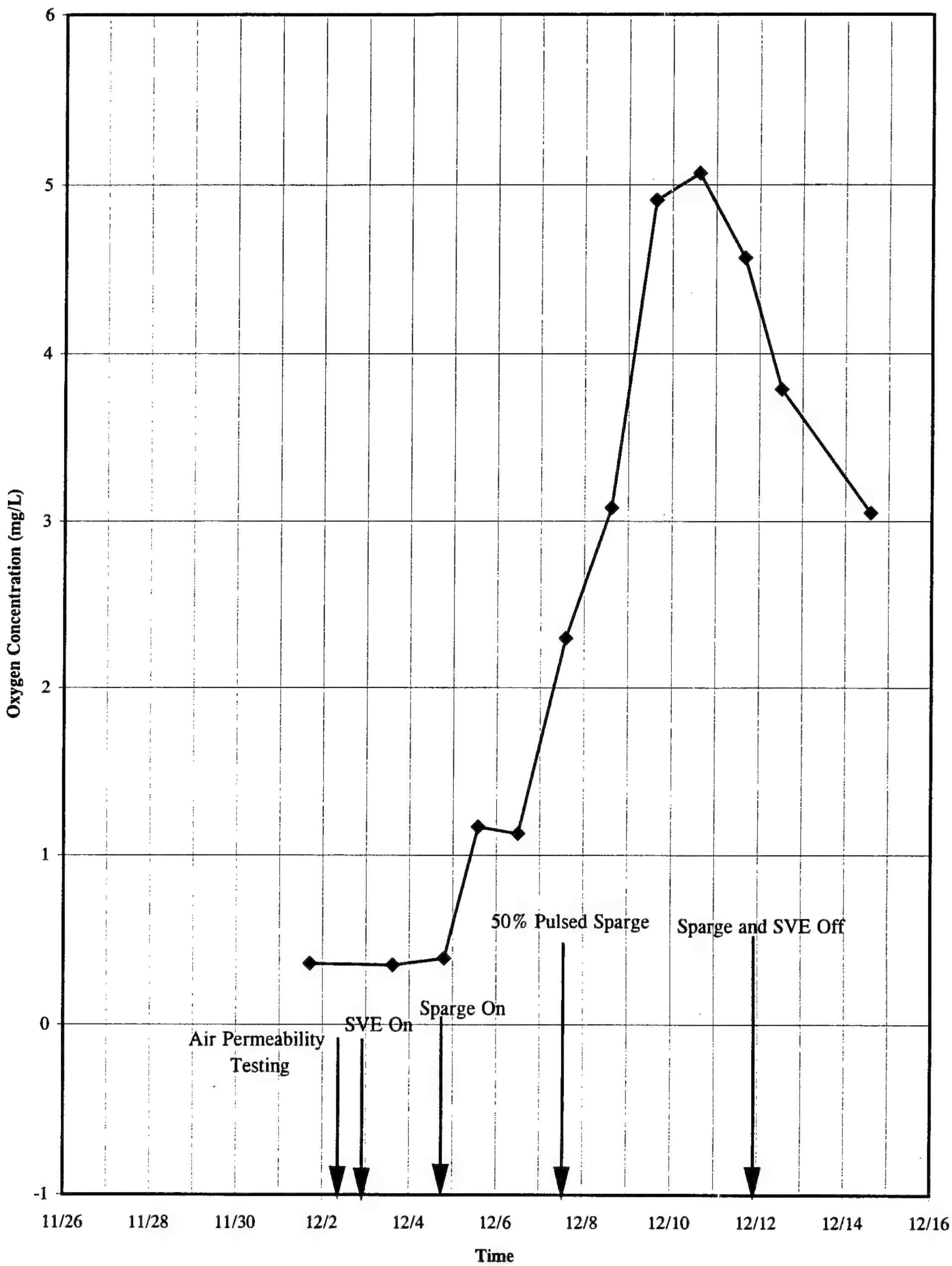


TABLE 6-3
SUMMARY OF DISSOLVED OXYGEN RESULTS
SITE SS-08 LOCATION B
WURTSMITH AFB, MICHIGAN

	Initial DO (mg/L)	Highest DO During Test (mg/L)	Highest DO Following Test (mg/L)	Lowest DO Following Peak (mg/L)
MP1C	0.49	5.37	13.36	---
MP1D	0.49	3.64	11.97	---
MP1E	0.43	5.76	8.54	1.25
MP2C	0.52	3.94	4.47	---
MP2D	0.47	1.09	1.12	---
MP2E	0.39	1.49	1.02	---
MP3C	0.35	5.07	3.79	3.05
MP3D	0.34	1.05	1.34	---
MP4C	1.47	10.11	11.39	---
MP4D	0.35	1.85	1.05	1.02
MP5C	1.60	3.91	3.42	2.98
MP5D	0.31	1.16	0.58	0.43

showed delayed reaction to the sparging. Data tables and time series plots of dissolved oxygen, ORP, and specific conductance for all of the monitoring wells are included in Appendix D.

These data indicate that air sparging was successful at moving oxygen to each monitoring well location, to distances of at least 40 feet from the sparge well. The deeper monitoring wells in close to the sparge well were apparently bypassed by the sparge air and received dissolved oxygen by diffusion from adjacent areas where sparge air channels developed. In general, the deeper level groundwater monitoring wells tended to become oxygenated to a lesser extent than the shallow (C level) wells.

An evaluation of the effect of pulsed sparging appears to be possible with this data set. Most of the wells showed an increase in the slope of dissolved oxygen gain when pulsed sparging began on December 7. Wells only showing an increase in the slope of dissolved oxygen gain following the start of pulsed sparging were MP1C, MP1D, and MP5C. Several wells showed initial gains in dissolved oxygen at the start of sparging, but dissolved oxygen concentrations started to decline in the remaining days of constant sparging. Following the change to pulsed sparging, the dissolved oxygen concentration in these wells began increasing again and typically increased through the remainder of the test. These wells were MP1D, MP2C, MP2D, MP2E, MP3D, MP4D, and MP5D.

The trend toward higher levels of dissolved oxygen during pulsed sparging is particularly significant given that the wells at greater depth (where less overall oxygenation was observed) were more likely to exhibit the improved oxygenation following the start of pulsed sparging. The increase in oxygenation seen in most of the wells after pulsed sparging began, is even more dramatic in light of the fact that it was attained at lower effective air injection rates. The air injection rate was kept constant when pulsed sparging began (at approximately 15 cfm), but the on time was only 50 percent, so the effective air injection rate was one half of the initial rate.

The pulsed sparging test at this site consisted of only one level of pulsing. This did not allow the evaluation of other potential pulsing levels. The use of only one pulse level was a deliberate attempt to better define if pulsing does provide improvement. The data support the use of pulsed sparging with a 50 percent on cycle. This level of pulsing also has the advantage of reducing the total system flow rate needs by 50 percent.

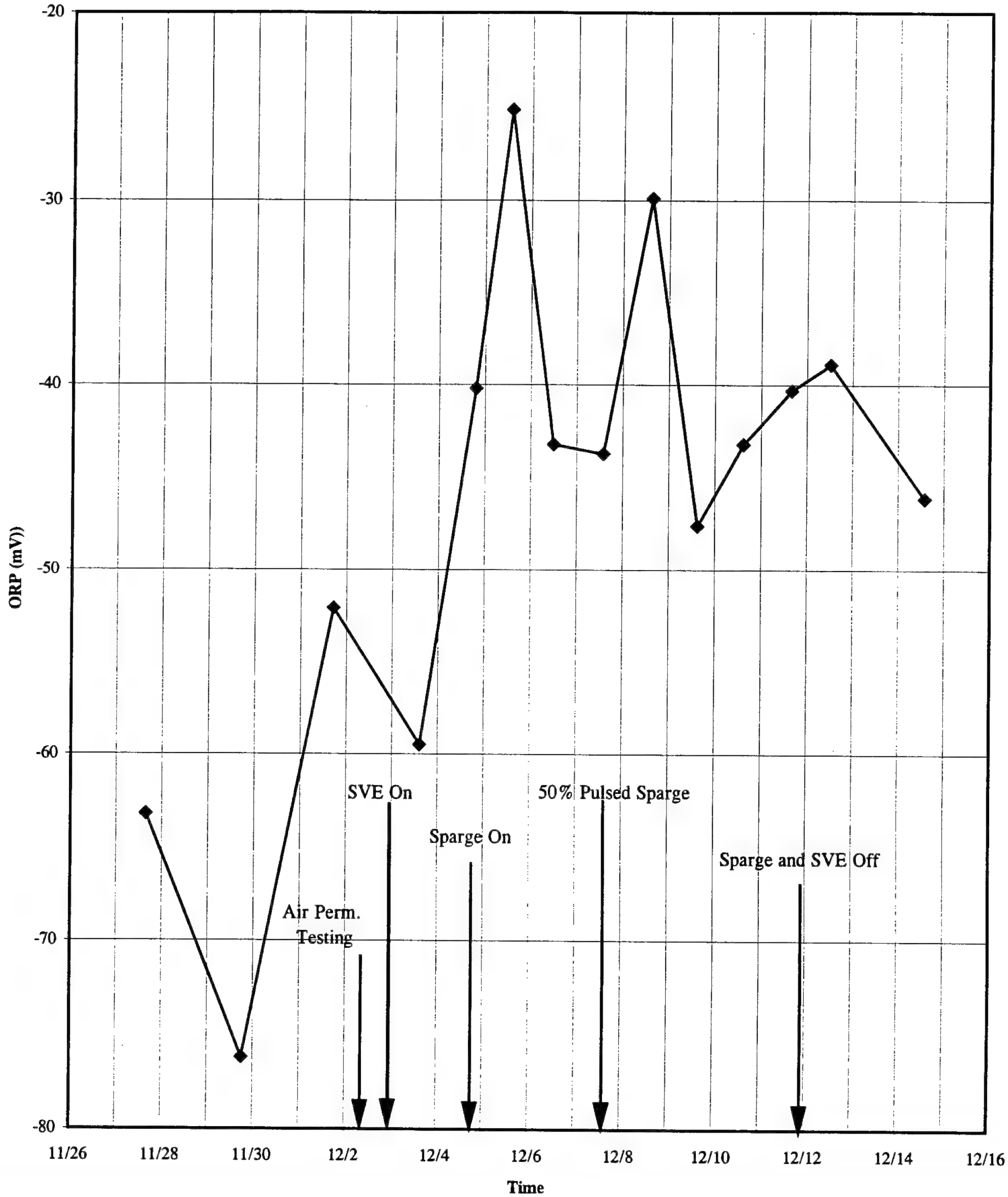
6.3.2 Oxidation-Reduction Potential Results

The general trend in the background ORP data at this site was toward decreasing ORP (more negative) with depth. This is similar to the trend observed at Site SS-06 and it may be due to the movement of oxygen from the vadose zone to groundwater. Deeper areas of groundwater not in contact with the vadose zone tend to have a lower ORP.

Time series plots of ORP for each of the monitoring wells are included in Appendix D. Figure 6-3 is an example of these plots for well MP3C. This figure shows an increase in ORP (more positive) following the start of sparging. It also shows a drop off in this increase through the period of constant sparging and an increase in the ORP after pulsed sparging begins.

The ORP results are less consistent than the dissolved oxygen results. In all cases, a trend toward increasing ORP during sparging was evident. However, considerable variability existed within this trend. In a few cases, the ORP data showed greater rates of increase or reversals in declining trends with the start of pulsed sparging. Overall the ORP data support the dissolved oxygen data regarding the effectiveness of air sparging, but the support provided by the ORP data is not as strong as that provided by the dissolved oxygen results.

FIGURE 6-3
OXIDATION-REDUCTION POTENTIAL FOR WELL MP3C
SITE SS08 LOCATION B
WURTSMITH AFB, MICHIGAN



6.3.3 Helium Results

Helium was included as a conservative tracer in the sparge air as discussed in Section 3. Helium does not dissolve to a great extent in the groundwater and should not interact with aquifer materials. When the sparge system is operated with a vapor extraction system, helium data can be used as an additional measure of the distance that sparge air has traveled away from the sparge well. Helium data for vadose zone monitoring are included in Appendix D.

Helium detection in the A level vadose zone wells is not expected. Helium that surfaces in the vadose zone would be expected to travel horizontally toward the extraction well for recapture. However, helium detection at the B level wells should be possible. For this test, only well MP1B consistently showed helium (see the data in Appendix D) while the AS/SVE systems were in operation. Well MP4B also showed the presence of helium in one monitoring event during the AS/SVE operation. These data do not provide support for the assertion that sparge air traveled consistently beyond the vadose monitoring well locations.

Recapture of helium by the vapor extraction system was relatively good. Over the period of AS/SVE operation, approximately 58 percent of the injected helium was recovered.

6.3.4 Sulfur Hexafluoride Results

Sulfur hexafluoride was used as an additional conservative tracer in the sparge air. Sulfur hexafluoride dissolves in groundwater to a degree somewhat greater than oxygen. Once dissolved in groundwater, it provides a good indication that sparge air was present at a given location. It does not interact with aquifer materials and it is not degradable within the aquifer. In addition, sulfur hexafluoride can be detected at very low concentrations.

Sulfur hexafluoride was injected into the sparge air at a concentration of approximately 0.3 percent. The equipment and methods for sulfur hexafluoride injection and the methods used

for sampling are discussed in Sections 2 and 3. Samples for sulfur hexafluoride analysis were taken three days after sparging began, just before the end of the air injection period and four days after the end of the air sparging test.

The results of the sulfur hexafluoride analyses are provided in Table 6-4. Sulfur hexafluoride was detected at most well locations at most sample times. The highest concentrations of sulfur hexafluoride were found in wells within the MP1, and MP2 clusters. Sulfur hexafluoride was not detected in MP2E at any of the sampling times. General trends toward increasing sulfur hexafluoride concentration with time are apparent at most locations.

These data suggest that sparge air was transported to most locations within the aquifer, but the quantity of air transport and contact with groundwater appears to be less than that observed at Site SS-06. The data indicating the arrival of sulfur hexafluoride at the most distant locations and in the deeper wells at these locations does support the dissolved oxygen and ORP data for sparging influence.

6.3.5 Soil Gas Constituents in Vadose Zone Monitoring Wells

Volatile organic compounds were of very low concentration prior to the start of vapor extraction and did not increase as a result of air sparging. Subsequent groundwater sampling at this site (for characterization of the hot spots) indicated that the volatile organic compounds concentration at this site is very low. The hot spot was apparently mischaracterized or it has moved in the time between characterization and this study. As expected, based on these results, the oxygen levels in the vadose zone soil gas were not significantly reduced, even before vapor extraction started.

Based on these findings, soil gas constituents could not be used to help establish the radius of sparging influence.

TABLE 6-4
SULFUR HEXAFLUORIDE ANALYTICAL RESULTS
SITE SS-08 LOCATION B
WURTSMITH AFB, MICHIGAN

WELL	12/7/97 SF6 (ug/L)	12/11/97 SF6 (ug/L)	12/14/97 SF6 (ug/L)
MP1C	160	93	380
MP1D	680	120	1400
MP1E	650	140	970
MP2C	260	210	560
MP2D	200	290	510
MP2E	<32	<32	<32
MP3C	84	220	190
MP3D	430	290	370
MP4C	110	80	210
MP4D	140	170	540
MP5C	<32	62	140
MP5D	<32	180	450

Sparging test began on 12/4/97 at 16:00 (constant rate sparging)
Pulsed sparging began on 12/7/97 at 15:30 (50% on time)
Sparging ended on 12/11/97 at 23:30

6.3.6 Stripping Capability of the Sparge Air

As discussed in Section 6.3.5, the volatile organic load in groundwater at this location was very low. As a result, the stripping capability of the sparge system could not be evaluated.

6.3.7 Sparging Radius of Influence

The methods used to determine the presence of sparge air within the aquifer suggest that air sparging was effective in most of the locations monitored. The most distant wells exhibited all of the characteristics of sparge influence, and wells located 360 degrees around the sparge well and at varying depths in the aquifer all exhibited sparge influence. Well MP2E was not effected by sulfur hexafluoride during this test. This is a good indication that sparge air did not come close to this well. MP2E did show a small increase in dissolved oxygen during the test. Given the low concentration of sulfur hexafluoride in the sparge air in comparison to oxygen, it is possible that oxygen diffused to this location but a sufficient concentration of sulfur hexafluoride did not. The detection limit for sulfur hexafluoride was 32 μg/L.

Based on these results it is concluded that sparging should be effective in most directions up to distances of 40 feet from the sparge well. It is likely that some sparge influence is present beyond 40 feet, but this can not be quantified using the data collected for this test. However, the effectiveness of sparging in reaching all areas and supplying significant quantities of oxygen is apparently not as good as at areas within Site SS-06.

Based on the need for some overlap between sparge locations to provide as complete areal coverage as possible, a distance between sparge wells of 50 feet is recommended for Site SS-08. The recommended net sparging flow rate is 11 scfm per well at 50 percent pulse cycle and the expected back pressure of a sparge well designed similar to S1 at this site will be 14 psi at start-up. Sparging using a 50 percent off time to provide pulsing is also recommended. This spacing and flow rate will allow overlap of sparging influence in most areas. The data

obtained from this test suggest that sparging should be effective at delivering dissolved oxygen to the groundwater for biodegradation in areas of SS-08 where significant volatile contamination is present.

6.4 VACUUM WELL SPACING FOR FULL SCALE SYSTEM

The appropriate spacing for the vacuum extraction wells was determined as follows. The air flow rate for a single extraction well, determined in Section 4.2 was 300 scfm. This rate allowed a near maximum flow rate from a single well without the steep increase in required vacuum observed at the next higher flow rate simulated (400 scfm). The air permeability soil characteristics discussed in Section 4.1, using the numerical model, were 55 darcies for horizontal permeability, 25 darcies for vertical permeability and for the permeability of the surface soil. The desired net sparging rate was 11 scfm for each well with sparge wells spaced 50 feet on center.

A numerical model was constructed with the above soil permeability characteristics. The model set-up was the same as described for site SS-06 with the addition of soil properties and conditions present at site SS-08 Location B.

The distance between the wells was adjusted to provide adequate capture of the sparge vapors. An extraction well spacing of 130 feet on center allowed for complete capture of sparge air. This spacing was reduced to provide a safety factor and to provide an easier design distance of 100 feet (twice the sparge well spacing).

The numerical model can be used to further optimize the design for full scale installation as discussed above for site SS-06. However, a maximum well spacing of 100 feet can be used without further modeling.

7.0 QUALITY ASSURANCE/QUALITY CONTROL PROGRAM

Quality assurance/quality control (QA/QC) measures implemented during this project were divided into three (3) categories: Field Quality Control, Laboratory Quality Control, and Data Verification and Validation. The Data Verification and Validation Summaries are included in Appendix E.

7.1 Field Quality Control

During sampling activities, several different types of field quality control (QC) samples were collected. The types of QC samples collected included: trip blanks, equipment blanks, ambient blanks, and field duplicates/replicates.

Field QA/QC samples were run throughout the field operation to ensure the quality and reproducibility of the data. As a general rule, QA/QC samples, in some combination, were run for every batch of samples. The QA/QC samples were run according to the following:

- One (1) trip blank was submitted to the laboratory with each cooler containing samples to be analyzed for volatile organic compounds (VOCs). The trip blank was used to determine if the samples were exposed to any contamination during transportation.
- Ten (10) percent of all soil samples collected were field replicates (two samples from the same point). These samples were collected to provide information about the heterogeneity of the soil.
- One (1) ambient blank per sampling event was collected and analyzed for VOCs only. These samples were collected downwind of active runways or other potential sources of VOCs where a sample potentially may have been affected.
- In accordance with MDEQ protocol, one (1) equipment blank was collected daily per sampling medium or at a frequency of approximately five (5) percent of the samples collected for the medium, whichever was more frequent. The analysis of the blanks served to verify the

cleanliness of the sampling equipment used. The equipment blank was analyzed for the same parameters as the samples collected with that equipment.

Decontamination of equipment was performed prior to collection of every sample throughout the field operation. Data Quality Objectives (DQOs) were met for all blank samples. Sampling probes were decontaminated between each sampling location.

Equipment used to measure field parameters was calibrated at the beginning of each work day and as necessary in accordance with manufacturer's recommendations.

Field custody procedures were established in the SAP to ensure that samples were not altered from the time of collection until laboratory receipt. Samples were labeled with a unique sample number in accordance with the sample identification scheme and a chain of custody form prepared. The chain of custody form was placed in zip-lock bags and taped to the inside of the cooler lid. The coolers were shipped to the laboratory with custody seals taped over the lids or the coolers were locked with a prenumbered tag.

7.2 Laboratory Quality Control

Methods to establish laboratory control limits were established in the laboratory's QAPP and incorporated into the project Work Plans.

Laboratory QC sample types are described below:

- Laboratory control samples (LCS) were analyzed for every batch of samples of similar matrix analyzed for inorganics. A batch was limited to not more than 20 samples of a similar matrix. The laboratory routinely uses the LCS for establishing the precision and accuracy of an instrument or procedure. An LCS contains a known quantity of a reference-traceable stock material in solution. The LCS solution is carried through the entire sample preparation and

analysis procedure and contains all of the analytes of interest for which the samples are analyzed.

- One (1) method blank was analyzed with each preparation batch of samples supplied from the field. The method blank was laboratory-pure, analyte-free water carried through the entire sample preparation and analysis procedure. The method blank was used to provide a check of background contamination due to sample preparation procedures.
- Matrix spikes (MS) and matrix spike duplicates (MSD) were performed for every 20 samples or every batch of samples. The chain of custody form designated the samples intended for MS/MSD analyses. The MS was used as a measure of accuracy and to determine if the sample matrix introduced a high or low bias to the data for each analyte spiked.
- All samples that required organic analysis by Gas Chromatography (GC) were spiked with an appropriate set of surrogate standards prior to sample preparation. The surrogate spikes measure recovery and serve as checks on any matrix interference exhibited by the samples.
- The laboratory's QAPP established methods for control limits. These control limits provide a range of expected values for each analyte.

Details of the laboratory and field QA/QC samples are reported in the Analytical Data as contained in Appendix E.

7.3 Data Verification And Validation

Data verification and validation (V&V) examines both the field and laboratory data. Data are reviewed in sufficient detail to determine the data usability, or level of confidence in the reported analytical results. The AFCEE QAPP, version 2.0 (January 1997) was the basis for the V&V process. Section 7.2 provides definitive guidance regarding the performance of data validation. The Data V&V summaries are included in Appendix E.

Specific parameters associated with the data were evaluated during the data validation process to determine whether or not the data quality objectives were met. Five (5) principal parameters (precision, accuracy, completeness, comparability, and representativeness) were addressed during the V&V process. Field sampling and handling procedures, laboratory analysis and reporting, and nonconformances and discrepancies in the data were examined to determine compliance with appropriate and applicable procedures.

The data evaluation process was divided into two (2) phases: data verification and data validation. The data verification process evaluated the following parameters:

- Specific Field Forms For Sample Collection and Handling,
- Chain of Custody Forms, and
- Completeness of Laboratory Data Deliverable.

The data validation process examined the analytical data to determine the level of confidence. General areas reviewed that apply to all chemical data included the following:

- Holding times,
- Proper Sample Preservation,
- Instrument calibrations,
- Calculation of results,
- Matrix spike/matrix spike duplicate recoveries,
- Laboratory/field duplication precision,
- Field/laboratory blank contamination,
- Dry weight correction for solid samples,
- Laboratory control samples, and
- Correct detection limits reported.

Specific Areas of evaluation for organic data included:

- Gas chromatographic/mass spectra (GC/MS) quality of volatile target compounds,

- Chromatographic peak pattern quality for benzene, toluene, ethylbenzene & toluene and MBTE,
- Surrogate recoveries,
- Internal standard area evaluations for volatile and semi-volatile data,
- GC/MS tuning for volatile and semi-volatile data,
- Relative percent difference between initial and continuing calibration response and calibration factors, and
- Identification of most usable data from dilutions and re-analyses.

Inorganic parameters that were evaluated included:

- Graphite furnace atomic absorption (GFAA) post-digestion spike recoveries, and
- Inductively coupled plasma (ICP) and GFAA performance checks
- LCS recoveries
- Matrix spike recoveries
- Laboratory duplicate precision
- Method blank contamination

Following the verification/validation process, qualifier codes were applied to specific data points, reflecting the level of confidence assigned to the particular datum. These codes included:

-- No qualification; the positive result or detection limit is confident as reported.

J Positive Result is estimated or imprecise; data point is usable for decision-making purposes. Positive results less than the Contract Required reporting limit are also qualified in this manner.

R Positive result or detection limit is considered unreliable - data point should NOT be used for decision-making purposes.

U Undetected result for analyte at the stated limit of detection.

UJ Undetected result; detection limit is considered estimated or imprecise; usable for decision-making purposes.

F The analyte was positively identified but the associated numerical value is below the Reporting Limit.

B The analyte was found in the associated blank, as well as in the sample.

M A matrix effect was present. Direction of bias may be indicated by M+ (biased high) or M-(biased low)

S This code applies to all field screening data

T Tentatively identified compound (using GC/MS)

Z This result, or detection limit in this analysis is not the best one to use; another analysis (e.g., the dilution or re-analysis) contain a more confident and usable result; refer to the report for more details.

Codes assigned by the laboratory include the following:

E Reported concentration exceeds the instrument calibration range and was subsequently diluted.

D Result reported from a diluted analysis, or surrogate or matrix spike compounds were diluted out due to sample dilution, and results could not be obtained.

J Result was below the reporting limit, but above the method detection limit.

I Interference caused by matrix effects; sample is often diluted to minimize such effects.

All data for this phase of the investigation were verified and validated as described above, and qualifier codes were applied to all affected data. In general, some data were qualified as estimated because of the following reasons:

- errors in result calculation for sulfur hexafluoride analyses
- analytical problems with the sulfur hexafluoride analyses
- low surrogate recoveries for volatile (BTEX) analyses
- high matrix spike/matrix spike duplicate recoveries for BTEX and MBTE analyses
- field duplicate imprecision
- continuing calibration verification recoveries that were not in control

In a few instances, results were qualified (B) because of trip blank contamination, and a few results were rejected (R) because of very poor surrogate recovery.

Data quality was acceptable for all analyses except for the sulfur hexafluoride analyses; significant laboratory problems (analytical method and calculation-related) caused the numerical results for all 81 samples to be considered biased quite low. Actual results are at least 20% higher than the laboratory values because of a calculation error. Values for a significant portion of the 81 total samples may be significantly higher than the known 20% bias due to loss of analyte during analysis. The extent of bias is unknown for several batches (see the Data Validation Summary Report).

8.0 WASTE MANAGEMENT

Waste generated during the field activities on this project consisted of the following:

1. Soil cuttings;
2. Waste water to include development, purge, decontamination water, and condensate generated during the pilot tests;
3. Spent carbon canisters;
4. Tubing used for development and purging of wells, including vapor and water sampling for field parameters;
5. PPE;
6. Other trash including bentonite chip and empty sand bags.

8.1 SOIL CUTTINGS

All contaminated soil generated during this project was classified as non-hazardous, petroleum-impacted soil. This wastestream included drill cuttings from vapor extraction wells, sparging wells and monitoring wells. Approximately 35 tons of petroleum-impacted soil was generated during this pilot test phase.

The drill cuttings were placed in sealed 55-gallon drums and labeled with the following information: site location, date generated and company name (AmTech Engineering). The drums at SS-06 pilot test area were stored in between the railroad and an access gravel road which bounds the test area. The drums at SS-08 pilot test area A were placed around the test area to protect the monitoring wells against any damages by vehicles using the apron area. The drums containing the soil cuttings from SS-08 pilot test area B were moved within the fenced area encloses Building 5092. This action was taken due to lack of space at SS-08 B area.

Due to the cold weather, moist/wet soil cuttings had frozen. Therefore, no sampling or disposal of soil was completed. These drums will be characterized and disposed during the installation of the remediation system which is scheduled in Spring 1998. The drums with PID readings exceeding the background by 10 ppm, will be emptied into a roll-off box. The emptied drums will be steam cleaned, repainted to cover the writings and will be left at the base for reuse. The rolloff box containing soil cutting will be transported for off-site disposal. The soils with less than 10 ppm will be spread on site, and the drums will be reused after steam cleaning and painting.

8.2 WASTE WATERS

Waste water generated during the decontamination of equipment, well development, purging of wells, field screening of groundwater, and condensate from the knock-out tank were collected in a mobile tank and transferred to a frac tank which was placed inside Building 5092. At the end of pilot test, one grab sample was collected and analyzed for VOC and metals which were the disposal parameters required by Oscoda Wastewater Treatment Plant (OWTP). The analytical results are included in Appendix E. Since the concentrations of above parameters met OWTP discharge criteria (Rule 57 limits), approximately 1,200 gallons of wastewater was discharged to the OWTP through a manhole in the Building 5092.

8.3 SPENT CARBON CANISTERS

The activated carbon canisters were used for off-gas treatment from the vapor extraction system. Each carbon canister was used until breakthrough which was detected by a PID (reading 1 ppm more than background). The spent canister were labeled to state site location, date generated, drum contents, and generator's name (AmTech). The canisters are stored around the test wells at each pilot test area.

A composite sample was collected from the spent carbon canisters from Pilot Test Area SS-06 and sent to DataChem Laboratory for the TCLP VOC analyses. The supplier of the carbon canisters had agreed to accept the spent carbon canisters for recycling without any disposal cost, if the TCLP VOC parameters were below the regulatory limits. Analytical results are attached in Appendix E. Since none of the VOC parameters were detected, the canisters will be shipped to the supplier during the next (installation of full scale system) mobilization.

8.4 TUBING, PERSONAL PROTECTIVE EQUIPMENT AND OTHER TRASH

The tubing used for development and purging of monitoring wells, and the tubing used for field measurements of vapor and water parameters was checked with a PID. Since the PID readings were less than 10 ppm, the tubing was discarded as normal refuse. Similarly, the used PPE was checked and discarded. Other trash generated to include empty bentonite chip and sand bags were also disposed as normal refuse.

9.0 CONCLUSIONS

The following conclusions are based on the results of the pilot tests. Conclusions are provided for each site individually.

9.1 CONCLUSIONS FOR SITE SS-06

1. Air sparging will be effective at this location for delivering oxygen to the aquifer for biodegradation and for air stripping contaminants from groundwater.
2. Soil vapor extraction will be effective for removing vapors from the vadose zone generated by air sparging and vapors present in the vadose zone from residual LNAPL present in the smear zone near the water table.
3. Air sparging without vapor collection will generate more volatile organic mass than can be degraded biologically in the vadose zone. If air sparging were to be practiced without vapor collection at this site, air emissions would exceed acceptable levels.
4. Design parameters for sparge wells include the following: (1) well grid spacing of 60 feet on center, (2) a pulsed sparging with 50 percent on cycle (based on results from Site SS-08 Location B), (3) net sparge rate per well of 11 scfm, (4) sparge well screen interval of 20 - 22 feet below the average seasonal water table, and (5) a pressure of 14 psi required at the wellhead.
5. Design parameters for vapor extraction wells include the following: (1) well grid spacing of 120 feet, (2) vapor extraction rate of 300 scfm per well, and (3) 50 inches of water column at the wellhead.
6. SVE vapor is expected to include up to 1 scfm of methane and other volatile compounds for each sparge well included in the radius of influence of the vapor extraction well. The expected VOC concentration (excluding light fraction VOCs) is up to 1000 ppmv of compounds other than methane.

9.2 CONCLUSIONS FOR SITE SS-08 LOCATION A

1. Soil vapor extraction will be effective at removing vapors from the vadose zone generated from air sparging. Air sparging test was not performed at this location, and same conclusion for Site SS-08 location B will be used for this location.
2. Collected vapors will include VOCs generated from sparging, but will not likely include a vapor load from the vadose zone (based on low VOC concentrations found in the vadose zone).
3. Design parameters for vapor extraction wells include the following: (1) well grid spacing of 100 feet on center under the tarmac, (2) vapor extraction rate of 250 scfm per well, and (3) 50 inches of water column at the wellhead.

9.3 CONCLUSIONS FOR SITE SS-08 LOCATION B

1. Air sparging will be effective at this location for delivering oxygen to the aquifer for biodegradation and for air stripping contaminants from groundwater.
2. Soil vapor extraction will be effective for removing vapors from the vadose zone generated by air sparging. SVE is necessary to avoid any risk of collecting explosive vapors underneath the adjacent buildings and tarmac/apron area.
3. Vapor load will consist of vapors extracted from groundwater with little or no contribution from the vadose zone.
4. Groundwater contamination at the location of this test was minimal. Soil contamination could not be detected with the methods used (no oxygen depression in the soil gas and no significant VOC detections during drilling or pilot testing).
5. Design parameters for sparge wells include the following: (1) well grid spacing of 50 feet on center, (2) a pulsed sparge rate with 50 percent on time, (3) net sparge rate per well of 11 scfm, (4) sparge well screen interval of 20 - 22 feet below the average seasonal water table, and (5) a pressure of 14 psi at the wellhead.

Design parameters for vapor extraction wells include the following: (1) well grid spacing of 100 feet, (2) vapor extraction rate of 300 scfm per well, and (3) 50 inches of water column at the wellhead.

10.0 REFERENCES

Air Force Base Conversion Agency, 1995. *Base Conversion Handbook: BRAC 95 Update.*

AmTech, 1997. Pilot test for installation of air sparging & soil vapor extraction at sites SS-06, SS-08, and ST-40, Wurtsmith Air Force Base, Michigan. October 1997.

Beckett, G.D., and D. Huntly, 1994. Characterization of flow parameters controlling soil vapor extraction. Groundwater. V32 : 239-47.

Cummings, T.R., Twenter, E.R., 1986. *Assessment of Groundwater Contamination at Wurtsmith Air Force Base, Michigan.* U.S. Geological Survey Water Resource Investigations Report 8C-4188.

Hantush, M.S, and C.E. Jacob, 1955. Non-steady radial flow in an infinite leaky aquifer. Transactional American Geophysical Union. 36(1):95-100.

Hantush M.S., 1961. Aquifer tests on partially penetrating wells. Journal of Hydraulics Div., Proceedings American Society of Civil Engineers., Hy5, pp. 171-195.

ICF Technology, Inc., 1995. *Draft Remedial Investigation Report: Site SS-08, Wurtsmith Air Force Base, Oscoda, Michigan.* July, 1995.

ICF Technology, Inc., 1997A. *Final Remedial Action Plan/Decision Document, Site SS-08, Wurtsmith Air Force Base, Oscoda, Michigan*, March 1997.

ICF Technology, Inc., 1997B. *Draft Final Feasibility Study Report, Sites SS-06, ST-40, SS-13, and OT-46.* January 1997.

ICF Technology, Inc., 1996. *Draft Remedial Action Plan/Decision Document, Sites SS-06, ST-40, SS-13, and ST-46, Wurtsmith Air Force Base, Oscoda, Michigan*, November 1996.

Johnson, P.C., M.W. Kemblowski, and J.D. Colthart, 1990. Quantitative analysis for the clean-up of hydrocarbon contaminated soils by in situ venting. Groundwater. V 28(3) : 413-29.

Massman, J.W. 1989. Applying groundwater flow models in vapor extraction system design. Journal of Environmental Engineering ASCE 115(1):129-49.

McWhorter D.B., and D.K. Sunanda,, 1977. Groundwater Hydrology and Hydraulics. Water Resources Publications, Littleton, CO. 256pp.

Theis, C.V. 1935. The relation between the lowering of the piezometric surface and the rate and duration of discharge to a well using groundwater storage. Transactions, American Geophysical Union. 2:519-524.

USAF, 1993. Draft Environmental Impact Statement - Disposal and Reuse of Wurtsmith Air Force Base, Michigan.

U.S. Army Corps of Engineers, 1995. *Soil Vapor Extraction and Bioventing*. Manual No. 1110-1-4001. November 1995.

USGS, 1983. (United States Geological Survey). *Groundwater Contamination at Wurtsmith Air Force Base, Michigan.*

USGS, 1990. (United States Geological Survey). Water Resources Division. *Installation Restoration Program Phase II - Confirmation/Quantitation Stage 2 Wurtsmith Air Force Base, Michigan: Hydrogeology Near Wurtsmith Air Force Base, Michigan*. January 1990.

WWES, 1994. (WW Engineering and Science). *Draft Remedial Investigation Report at the ACC Operational Apron: Aircraft Parking Spot 19 (SS-53)*. January, 1994.